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INNOVATIONS in earthquake risk reduction for resilience: RECENT advances and challenges

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INNOVATIONS IN EARTHQUAKE RISK REDUCTION FOR RESILIENCE: RECENT ADVANCES AND CHALLENGES

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ABSTRACT

The *Sendai Framework for Disaster Risk Reduction 2015-2030* (SFDRR) highlights the importance of scientific research, supporting the *'availability and application of science and technology to decision making'* in disaster risk reduction (DRR). Science and technology can play a crucial role in the world's ability to reduce casualties, physical damage, and interruption to critical infrastructure due to natural hazards and their complex interactions. The SFDRR encourages better access to technological innovations combined with increased DRR investments in developing cost-effective approaches and tackling global challenges. To this aim, it is essential to link multi- and interdisciplinary research and technological innovations with policy and engineering/DRR practice. To share knowledge and promote discussion on recent advances, challenges, and future directions on *'Innovations in Earthquake Risk Reduction for Resilience'*, a group of experts from academia and industry met in London, UK, in July 2019. The workshop focused on both cutting-edge *'soft'* (*e.g.,* novel modelling methods/frameworks, early warning systems, disaster financing and parametric insurance) and *'hard'* (*e.g.,* novel structural systems/devices for new structures and retrofitting of existing structures, sensors) risk-reduction strategies for the enhancement of structural and infrastructural earthquake safety and resilience. The workshop highlighted emerging trends and lessons from recent earthquake events and pinpointed critical issues for future research and policy interventions. This paper summarises some of the key aspects identified and discussed during the workshop to inform other researchers worldwide and extend the conversation to a broader audience, with the ultimate aim of driving change in how seismic risk is quantified and mitigated.

Keywords: *Earthquake Risk reduction; Earthquake Risk Modelling; Physics-based ground-motion modelling; Earthquake Early Warning; Parametric Insurance; Seismic Isolation; Supplemental Damping; Non-structural components; Structural Health Monitoring.*

1. INTRODUCTION

The *Sendai Framework for Disaster Risk Reduction 2015-2030* (SFDRR)[1], which the United Nations endorsed in 2015, is a comprehensive framework with four priorities for action and seven achievable targets for disaster risk reduction (DRR) worldwide. Two of those four priorities are: *1)* understanding disaster risk; and *2)* investing in DRR for resilience. The overall goal is to reduce direct economic loss and the number of people affected, minimise damage to critical infrastructure by increasing their resilience, and improve the dissemination of disaster risk information, all to be achieved by 2030.

The SFDRR identifies an urgent need for coordinated global efforts by governments, researchers, and practitioners to reduce natural-hazard risks by prioritizing disaster preparedness over post-disaster management,

[1] https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

which is an important step forward for most nations, especially low-income countries. It also stresses the importance of improving the understanding of the complex interplay of hazard, exposure, vulnerability, and capacity (*i.e.*, 'all the strengths, attributes and resources available within a community, organization or society to manage and reduce disaster risks and strengthen resilience'; UNDRR Terminology, updated February 2017[2]) as well as risk drivers such as poverty, climate change, population growth in hazard-exposed areas and uncontrolled urbanization, among others. To this aim, the SFDRR calls for the promotion of scientific research, supporting the *'availability and application of science and technology to decision making'* in DRR. There is a clear need to link multi- and interdisciplinary research and technological innovation to policy and engineering/DRR practice.

Between 2000-2019, 7,348 natural hazard-related disasters have been recorded worldwide by the Emergency Events Database (EM-DAT)[3], one of the leading international disaster databases. These events have claimed approximately 1.23 million lives (an average of 60,000 per annum), impacted over four billion people, and resulted in ~US$ 2.97 trillion (adjusted for inflation to reflect US$ in 2019) in economic losses. Globally, floods and storms were the most frequent natural hazard-related disasters, accounting for 44% and 28%, respectively, of the total events between 2000 and 2019. Geophysical hazards, such as earthquakes and volcanic activity, made up a total of 9% of all events, the majority of which are earthquakes (inclusive of tsunamis). Despite their relatively low frequency, earthquakes and tsunamis have typically been the deadliest form of disasters in the past two decades, accounting for 58% of the total fatalities. The 2015 earthquakes in Nepal (8,969 deaths) and the 2018 earthquake in Palu, Indonesia (4,340 deaths) are two recent examples of earthquakes' deadly potential. Furthermore, earthquakes have consistently led to severe economic losses and caused substantial damage to infrastructure.

Although earthquake-risk awareness is increasing among the public and governments worldwide, there remains a strong need to advance risk and resilience assessment frameworks, models, methods, and their implementation tools to support DRR decision making (*e.g.*, on the prioritisation of assets requiring seismic strengthening and, more in general, the design of optimal DRR strategies) and foster more resilient societies, in line with the SFDRR. This is a crucial task for seismically active regions where there is a convergence of high seismic hazard, vulnerability, and exposure, and where low-probability, high-consequence events can have catastrophic impacts on critical infrastructure such as nuclear power facilities. A pertinent example is the 2011 Tohoku earthquake and tsunami in Japan, which caused US$ 239 billion in financial losses (2011 value), the highest figure for any disaster event on record[4]. In this context, probabilistic risk models, which estimate potential human and economic losses from natural hazards, together with novel structural and non-structural technologies, are essential tools for effective pre-disaster preparation and financial planning to reduce disaster risk and improve resilience.

To share knowledge and promote discussion on recent advances, challenges, and future directions of '*Innovations in Earthquake Risk Reduction for Resilience*', a group of experts from academia and industry met in London, UK, in July 2019. The workshop focused on cutting-edge *'soft'* (*e.g.*, novel modelling framework, early warning, disaster financing and parametric insurance) and *'hard'* risk-reduction strategies (*e.g.*, novel structural systems/devices for new structures and retrofitting of existing structures, sensors) for the enhancement of structural and infrastructural earthquake safety and resilience. Emphasis was also placed on applications for low-income countries: low-income nations tend to be disproportionately affected by natural hazards due to a lack of coping mechanisms, which, in turn, inhibits progress on poverty alleviation and slows long-term economic development (*e.g.*, [1]).

This paper summarises some of the key findings from the 2019 workshop. These include a collection of thought-provoking state-of-the-art reviews, opinions, and discussions to promote conversations beyond the workshop and contribute significantly to an enhanced understanding and management of earthquake risk. The paper is organised as follows. *'Soft'* risk-reduction strategies are first discussed in Sections 2 to 4, while *'hard'* strategies are the focus of Sections 5 to 8. Section 2 introduces earthquake risk, and resilience quantification approaches, promoting the use of physics-based ground-motion simulation for seismic hazard assessment, debating the need for advanced loss modelling approaches and consideration of hazard interactions. Section 3 presents parametric insurance approaches for earthquake risk. Section 4 highlights recent advances and perspectives in earthquake early warning and its engineering applications. Section 5 discusses the use of seismic isolation systems and supplemental damping devices for increasing structural resilience. Section 6 examines some innovative aspects related to self-centring and rocking

[2] https://www.preventionweb.net/disaster-risk/concepts/capacity
[3] https://www.emdat.be
[4] https://www.undrr.org/publication/human-cost-disasters-overview-last-20-years-2000-2019

systems. Section 7 focuses on innovative non-structural components, with emphasis on external building partitions. Section 8 describes the latest advances in structural health monitoring. Section 9 discusses additional challenges related to low-income countries. Some key highlights from the paper and concluding remarks are finally provided in Section 10.

2. QUANTIFYING EARTHQUAKE RISK

Quantifying the potential impacts of natural hazards on buildings, infrastructure, and people located in hazard-prone regions is of primary interest to various stakeholders, such as local/central government agencies, property owners/managers and (re)insurance companies, among others. It is critical that potential loss estimates, on which risk management and DRR/resilience-increasing decisions rely, are as accurate as possible given the available information and the associated uncertainties.

Catastrophe risk models are popular tools for estimating potential losses due to natural hazards. Until the 1980s, portfolio loss estimates associated with natural hazards such as earthquakes, windstorms, and floods were usually extrapolated from historical loss data. These estimates were severely biased, given the limited span covered by historical catalogues, the lack of systematically and reliably measured/reported loss data, and the dynamic changes to exposure in high-risk regions around the world. As a result, purely actuarial approaches for the estimation of losses generated by rare natural hazards (*e.g.*, based on claims data as in the case of automobile or fire insurance policies) have been progressively abandoned in favour of simulation-based models that integrate all relevant science, data, and engineering knowledge. Specifically, these models incorporate detailed datasets and scientific understanding of the highly complex physical phenomena related to natural hazards and engineering theory quantifying the hazard-induced response of buildings/infrastructure and their contents (*e.g.*, [2]). Moreover, uncertainty lies at the heart of catastrophe risk modelling and requires explicit consideration at all modelling stages. Thus, probabilistic approaches are nowadays widely used to model the complexity of natural hazards and their impact on the built environment.

The general framework for modelling the impact of natural hazards on asset inventories can be broken down into the following four primary components, or modules, consistent with the general catastrophe risk modelling framework (*e.g.*, [2]): *(a)* hazard, *(b)* vulnerability, *(c)* exposure, *(d)* loss – as shown in Figure 1. Each module requires substantial amounts of data for model development and validation by considering both physical and socio-economic factors.

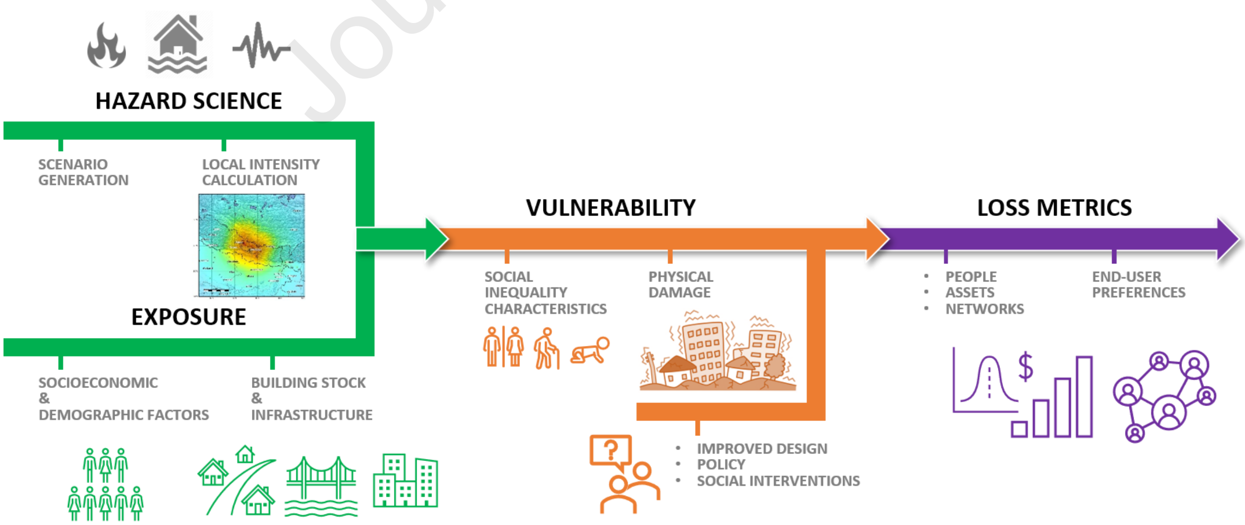

Figure 1. Disaster-risk model components. An exposure module contains details on the location and characteristics of the (existing) inventory at risk, possibly including human exposure to death or injury. The hazard module generally deals with representative hazard scenarios, assessing their resulting intensities across a geographical area under consideration. The vulnerability module quantifies the susceptibility to damage or other forms of loss to structures/infrastructure and their contents. Typically, vulnerability is confined to direct economic losses, often

described in terms of repair/replacement costs. In some cases, social aspects of vulnerability are also considered (often simplistically). The main output of a risk model is a description of the annual probability of exceeding certain economic loss levels and related statistics.

In recent decades, significant progress has been made in understanding the impacts of earthquakes on the built environment, based on scientific and technical contributions from the fields of geology, seismology, engineering, statistics and social science. More in general, disaster-risk quantification has continually evolved based on lessons learned from historical events, new hazard and engineering research/models, and improved technology, enabling the more realistic representation of perils like floods that were computationally infeasible to model in the past. Despite this, the state-of-the-art in natural-hazard risk assessment still suffers from various shortcomings related to modelling, data and some underlying assumptions (*e.g.*, [3]).

In particular, risk-mitigation planning due to earthquake-induced hazards (from ground motion, landslide, and liquefaction, among others) and the development of related emergency response and recovery strategies still require improvements in the computational ingredients of the seismic risk assessment process. Three specific challenges related to *(a)* earthquake-induced ground-motion modelling in seismic risk assessments, *(b)* earthquake-induced loss and business interruption modelling, and *(c)* resilience quantification of systems exposed to multiple hazards (including earthquakes) are discussed in this section.

2.1 Ground-Motion Modelling for Seismic Risk Analysis

Ground-motion footprints and their associated uncertainty are critical ingredients for understanding the potential extent of earthquake-induced damage and resulting losses. Therefore, accurate quantification of seismic hazard is crucial for building communities capable of effectively withstanding and recovering from the physical and societal impacts of earthquakes. Ground-motion amplitudes are typically estimated for scenario and probabilistic seismic hazard analyses using ground-motion models (GMMs). These models are based on statistical regressions of regionally or globally recorded ground motions from past events. Naturally, such recorded motions have been made available only during the 20th century, and they are not even uniformly distributed within this period and in space. However, their number is rapidly increasing. For instance, recent NGA-West2 [4] GMMs are mainly based on recordings from California, Italy, Taiwan, Iran, and Turkey. Interestingly, despite the relative increase in the number of recordings (*i.e.,* potential data points for model calibration) and the increase in the complexity of GMM functional forms since the 1970s[5], the uncertainty in the estimates from GMMs has not decreased [5] due to two main inherent shortcomings. Firstly, empirical GMMs are affected by a scarcity of recordings from large-magnitude ruptures in the near-fault region due to the low occurrence frequency of these ruptures and the lack of nearby strong-motion recording instruments. Secondly, GMMs consider simplified representations of the rupture process on the fault (*i.e.,* source), the propagation of seismic waves through the crust and sedimentary layers (*i.e.*, path), and the non-linear sub-surface soil response (*i.e.,* site) effects [6]. Hence, these models provide limited means to scrutinize the region- and site-specific interplay of physical parameters (and their uncertainty) that affect the resulting ground motion and geohazards (*e.g.,* liquefaction, landslide). For instance, conventional empirical GMMs may not succeed in robustly addressing the following three issues:

1) *Spatial correlation and cross-correlation of ground-motion characteristics:* GMMs do not explicitly address the correlation between a given ground motion intensity measure (IM) at different locations and the cross-correlation between different IM types (at other sites). For instance, underestimating ground-motion spatial correlation features results in an underestimation of damage/losses from rare events and an overestimation of damage/losses from frequent events. This may lead to biased risk metrics, with negative implications on disaster prevention plans [7]. Conventionally, this shortcoming of empirical GMMs necessitates the use of *ad-hoc* empirical models to incorporate the spatial [8] and cross-IM [9] correlations, often increasing the total epistemic uncertainty in ground-motion estimates of empirical GMMs. In addition, existing spatial correlation models are limited by strong assumptions about the isotropy (*i.e.*, direction-independence) and stationarity of spatial properties [10].

2) *Directivity and directionality:* Superposition of seismic waves in the close vicinity of a fault can result in velocity pulses in the recorded ground motions that may cause large damage to systems with pertinent dynamic characteristics [11]. Since the most advanced GMMs in the literature [12] do not explicitly represent these effects - referred to as directivity pulses - attempts have been made to model this phenomenon using *ad-hoc* models [13].

[5] http://www.gmpe.org.uk

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There are large uncertainties in the estimates from these directivity models, due to the limited number of directivity-induced pulse-like ground motions found in empirical databases and the uncertainties associated with representing directivity phenomenon [13]. In addition, ground-motion properties (*i.e.*, amplitude, frequency content, and duration) are functions of the direction in which they are recorded or rotated during their processing. Such directionality and directivity effects are linked, as the horizontal direction of the largest long-period motion is generally close to the direction with the largest directivity velocity pulse. While directivity velocity pulses are mainly a source effect in the close vicinity of faults and depend on the source-to-site geometry, directionality is a source-path effect. It depends on heterogeneity in both the rupture and the soil media through which waves propagate. The spatial correlation of ground motion IMs also depends on the directionality and directivity phenomena. Since the occurrence of directivity effects (in the near-fault region) and direction-dependent ground motion properties (in the near- and far-field regions) may induce larger seismic demand on both ordinary and critical structures, addressing these effects is crucial for engineering/risk assessment applications.

3) *Displacement demand in the fault vicinity:* Various critical structures and extended infrastructure such as lifelines, may cross or be located close to fault zones and, in some instances, may be buried under the ground surface [14]. Co-seismic displacement of faults (*i.e.*, due to the arrival of earthquake waves) is conventionally estimated via geological and seismological approaches and typically presented in community seismicity models, *e.g.*, SHARE (Seismic Hazard Harmonization in Europe) [15]. Off-fault transient and residual displacements in the vicinity of faults are also essential factors in assessing seismic risk to engineered systems located close to fault zones. Variation in rupture characteristics (*e.g.*, localized high slip) can significantly affect these displacements. Difficulties in accurately obtaining displacement metrics from recorded ground motions due to their sensitivity to filtering and correction processes [16], and the scarcity and spatial sparsity of data in the near-fault region limit the development of robust ground-displacement models. Recent research has also shown, both numerically and experimentally, that geotechnical and/or geological discontinuities can cause significant differential axial deformation that may buckle buried pipelines, in contrast to the current perception that transient ground displacements does not induce noticeable seismic demands [17]. Along these lines, validated ground displacement models are required for assessing the damage and risk to infrastructure as well as for geohazard analyses such as slope stability.

To resolve the above shortcomings in hazard quantification and reduce the resulting uncertainties (and their propagation to risk metrics), validated physical models representing source, path, and site effects should be employed, together with high-fidelity simulations of the earthquake rupture and wave propagation phenomena. Despite the long history of numerical simulations, such as purely stochastic methods based on random vibration theory or Green's function methods [18], the physics-based approach to ground-motion modelling demonstrates higher predictive capabilities. This uses site- and/or region-specific data to explicitly model the physical process of slip and its heterogeneity, the rupture evolution in time and space, the wave propagation in the Earth's crust and basin generated waves, and non-linear sub-surface soil response, among other features [6,19–24]. It therefore provides an analyst with a robust means of explicitly addressing aleatory variability in the underlying parameters and epistemic uncertainty due to the range of scientifically plausible models. Figure 2 illustrates the development stages of the physics-based ground-motion modelling approach, in which the current knowledge of tectonics and seismicity is incorporated in regional seismicity models to generate realizations of potential earthquake events, then used in regional ground motion simulations and risk assessment.

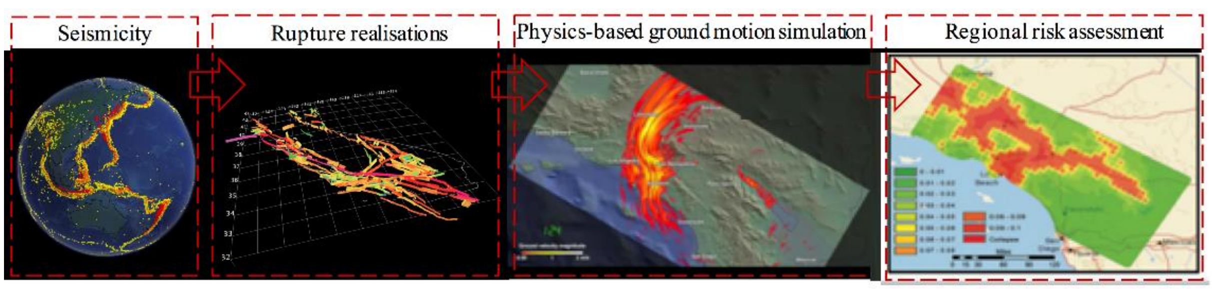

Figure 2. Computational stages of the physics-based approach to modelling ground motions, from the tectonics and seismicity models to rupture realizations of potential events and the subsequent ground motion simulations and risk assessments (adapted from Jones *et al.* [25] and the SCEC Community Fault Model[6]).

Recent advances in high-performance computing have facilitated large-scale physics-based ground-motion simulations. Notably, the Cybershake projects in California [26] and New Zealand [27] have attempted to leverage the physics-based simulation methodology for the purpose of seismic hazard analyses on large geographical scales. In addition to hazard assessments, simulated ground motions provide a valuable supplement to empirical ground motions when selecting record ensembles for response-history dynamic analysis of structural and geotechnical systems, within the framework of performance-based earthquake engineering [28]. The Shakeout [29] and Haywired [30] projects, conducted for prospective earthquake scenarios in California, have used the physics-based simulation methodology to assess the hazard and subsequent damage and structural risks to different types of structures and distributed infrastructure systems, as well as economic and societal impacts, disaster recovery, and preparedness for future events. For these scenario-based hazard and loss assessments, simulated ground motions explicitly represent the correlation and cross-correlation of ground-motion IMs across large geographical extents without additional modelling, and most importantly, without the need to further capture directivity and basin effects.

There is a general concern among engineers and risk modellers that simulated ground motions may not be 'equivalent' to real records in estimating seismic demands, which propagates a degree of uncertainty in estimating the induced damage and loss/risk metrics to structures and infrastructure. To this end, a significant amount of research has been carried out in recent years to validate ground motion simulation methods for engineering applications (*e.g.*, [31–36], to name a few). These validation efforts highlight the similarities and differences between simulated and recorded ground motions, which can assist in improving the simulation methods by identifying limitations in the input rupture and velocity structure models. A technical activity group of SCEC (Southern California Earthquake Center) is focused on developing and implementing testing/rating methodologies for ground motion validation, based on collaborations between ground-motion modellers and engineers. Validation studies completed to date have demonstrated that physics-based simulation methods are sufficiently capable of being used for the purpose of seismic hazard and risk assessments.

The risk modelling industry has also been interested in the development and utilization of physics-based ground motion simulations. For instance, the Willis Research Network (WRN), which is an award-winning collaboration scheme between academia, finance and insurance industries, has conducted a pioneering investigation that examined how physics-based 3D ground motion simulation techniques can support decision-making in the (re)insurance industry, by capturing phenomena that current catastrophe models tend to oversimplify [37]. This study demonstrated that using 3D simulations (rather than empirical models) for moment-magnitude M 9.0 scenarios in the Cascadia subduction zone reduces the uncertainty in the loss estimates, yet captures more detailed spatial ground-motion and loss characteristics. For instance, the study found that specific locations around Seattle and Vancouver are characterised by significant ground-motion amplifications, while other sites are characterised by opposite features, in a way that is not typically captured by the empirical GMMs employed in conventional loss assessments (see Figure 3). Moreover, loss estimates resulting from 3D ground-motion simulations are characterized by much lower volatility than in conventional catastrophe models, thus allowing more accurate and more reliable decision making. Findings from these types of studies can provide various stakeholders with higher confidence in tail risk assessment and portfolio optimization, helping them to make more informed reinsurance purchases and build more accurate internal models.

From a modelling perspective, one of the main challenges for conducting physics-based ground motion simulations is the fine spatial resolution required for the velocity model in the deep crustal layers and shallow near-surface depths [38]. The acquisition of high-resolution data requires large investments from stakeholders, which will have direct returns in terms of accurate ground-motion estimates for seismic design, risk assessment and DRR. Another critical challenge in developing high-fidelity simulation methods involves improving the understanding of the interplay of the tectonic stress state and the mechanics of co-seismic slip, so that realistic rupture models can be established. Both modelling issues remain extremely challenging for regions with scarce seismological, geophysical, and geotechnical data, such as low-income countries. The development of more economical data acquisition devices and more efficient testing and analysis methods can help to alleviate some of these challenges. Accurately capturing

[6] https://www.scec.org/research/cfm

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the high-frequency content of the ground motion, which is currently dependent upon the use of phenomenological approaches, can also benefit from high-density data acquisitions [39].

From a practical engineering perspective, difficulties accessing simulated ground motions is also a significant challenge to overcome. The recently released SCEC broadband platform [40] provides scientists and engineers with open-source tools to obtain ground motions simulated for California. Similar efforts are also being made in Italy, through a web repository (SYNTHESIS: SYNTHEtic SeISmograms database) that contains simulated waveforms for Italian earthquakes based on different simulation techniques [41], as well as in New Zealand, through SeisFinder by QuakeCoRE (New Zealand Centre for Earthquake Resilience)[7]. These efforts can assist with rapidly adapting simulated ground motions to engineering and risk modelling practices and provide a medium for the validation-revision interaction between the end-users and ground motion modellers that accelerates the improvement of simulation methodologies [42].

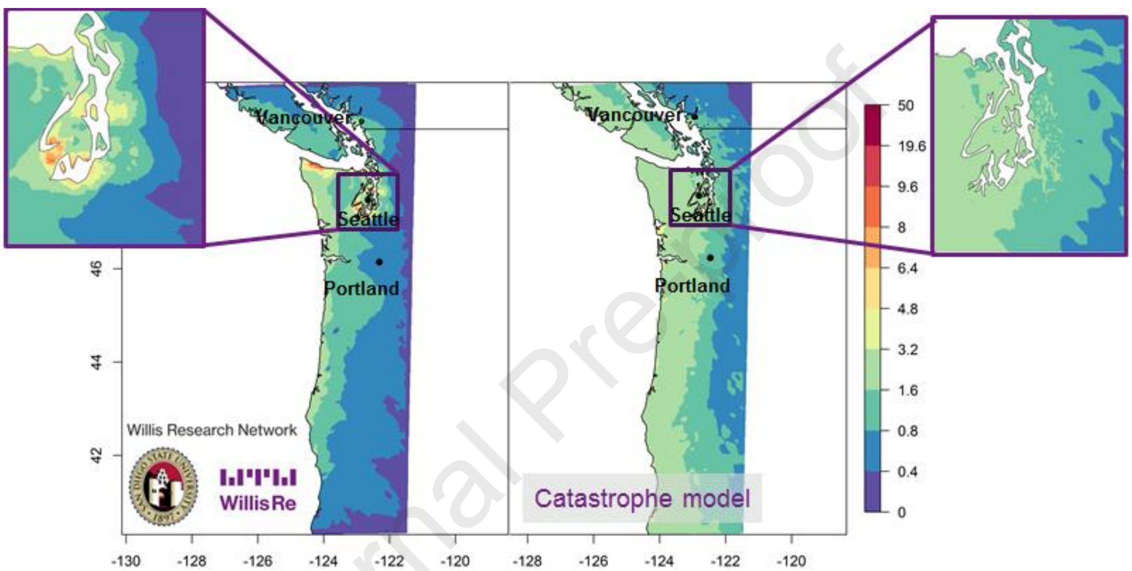

Figure 3. Spectral acceleration at 3 sec (in m/s^2) from a M 9.0 scenario predicted by 3D ground motion simulation (left), compared to an equivalent scenario from a GMM (right). The differences in ground motion from the two approaches are highlighted for the Seattle region (adapted from Papaspiliou *et al.* [37]).

While the efforts mentioned above show that 3D physics-based ground motion simulations represent a viable alternative to empirical GMM outputs for capturing earthquake hazard and the associated risk, there is still a number of challenges that need to be tackled for a full implementation of this methodological shift in large-scale seismic risk modelling. For example, these simulations require a long pre-processing and execution time, making it unfeasible for modelling all stochastic events within a catastrophe model catalogue. This explains why they have only been used in catastrophe risk assessments for a few extreme scenarios (*e.g.,* M 9.0 in Cascadia [37]). The lower predictive power (*i.e.,* questionable validity) of simulated ground motions in the high-frequency range represents another obstacle to their use in large-scale regional risk assessments. Overall, understanding and capturing all potential sources of ground-motion uncertainty and constraining all input parameters within reasonable bounds is an on-going research endeavour, which is crucial for accurately representing seismic hazard and resulting economic and social losses.

2.2 Advancing Earthquake-Induced Loss Modelling

Losses traditionally quantified by earthquake risk models include repair cost, disruption time, and the number of casualties. State-of-the-art loss metrics that have recently been developed for earthquake loss modelling include *(a)* the environmental impact of restoring structures to their pre-earthquake condition [43,44]; and *(b)* well-being loss [45], which accounts for the uneven effects of the post-disaster recovery period across different socio-economic

[7] http://www.quakecore.nz/seisfinder-a-portal-for-earthquake-resilience-simulation-outputs

groups in society. Earthquake loss models may be structure-specific or regional in scale, relating to portfolios (or classes) of similar structural typologies. A state-of-practice approach to the former is the FEMA P-58 methodology [46], which was developed to assess the seismic performance of individual buildings in the U.S and incorporates component (*i.e.*, structural and non-structural elements and building contents) level fragility/loss modelling. The HAZUS [47] methodology is a popular regional model that has been employed to quantify earthquake losses all over the world, including the US [48], Canada [49], India [50], Venezuela [51], and Israel [52].

Given the widespread use of earthquake loss models in engineering and risk analysis practice, it is crucial to understand whether the underlying calculations are realistic enough, so that required improvements can be identified, and models can be advanced accordingly. Numerous successful efforts have been made in the literature to validate the loss predictions of regional loss models. These include the work of Spence *et al.* [53], which found that two different methodologies overestimated the losses caused by the 1999 Kocaeli earthquake in Turkey at near-fault sites. Further attempts at regional loss model validation are the study by Wald *et al.* [54], which concluded that HAZUS tends to overestimate losses from earthquakes with magnitudes less than or equal to M 6.0, and the work of Lin *et al.* [55], which determined a need to improve New Zealand-specific earthquake loss modelling. On the other hand, a relatively small number of studies have focused on evaluating structure-specific earthquake loss models. For example, one of the very few attempts to evaluate FEMA P-58 loss predictions has been the work of Cremen and Baker (2019) [56]. They proposed a methodology that focused on non-structural component-level loss predictions of FEMA P-58 and used information collected on rapid damage surveys conducted after earthquakes in New Zealand and California. The evaluation procedure specifically determined whether FEMA P-58 loss predictions or ground-shaking observations provided more insight into damage, for a large set of buildings. It was found that the loss predictions perform better than the ground-shaking observations and are particularly beneficial when there is small spatial variation in ground shaking between buildings. While the results of this study offer an understanding of the degree to which FEMA P-58 loss calculations reflect real-life consequences of earthquakes, the investigations were limited to examining relative rankings of loss predictions across a set of buildings, since the damage surveys used did not provide enough information to directly assess the predictions in a more robust, quantitative manner.

A better evaluation of structure-specific loss models would involve more complete asset data, and direct validation of the loss predictions, but it is difficult to obtain the necessary high resolution structural/non-structural and related earthquake consequence information; even repair cost data is challenging to acquire, as any available related information is likely to include the cost of upgrades and other expenditure not related to repair works. This type of evaluation has been carried out for FEMA P-58 using buildings in Italy [57], for which the repair costs and building information were obtained from a comprehensive database of residential buildings damaged by the 2009 L'Aquila earthquake [58]. However, the study was limited to five reinforced concrete buildings and the significant differences between US and Italian construction standards made it difficult to evaluate the repair cost predictions using default FEMA P-58 component fragility functions. In addition, the data used in the Italian case were not immediately available after the earthquake, due to the notable time required for data collection and processing. An ideal evaluation of structure-specific loss predictions would involve high-resolution post-earthquake consequence data for assets in the region where most of the information used to construct the relevant model's component fragilities and loss functions has been collected. A limited amount of repair cost and recovery time data is available for buildings damaged in the 2014 South Napa earthquake [59], but there needs to be further investigation to determine if the corresponding building and ground motion information available is sufficient for accurate modelling in FEMA P-58. Building databases such as the recently compiled Tall Buildings Safety Strategy inventory in San Francisco Council (2018)[8], the University of California, Berkeley building inventory compiled by Comerio [60–62], as well as the case study inventory of Los Angeles non-ductile concrete buildings developed by Anagnos *et al.* [63–65] and Comerio and Anagnos [66], will offer valuable opportunities to validate (and thus advance) structure-specific loss predictions in future California earthquakes, if comprehensive consequence and ground motion data can also be obtained.

Structure-specific repair time predictions have the potential to play an important decision-making role in seismic resilience assessments, given their ability to pinpoint unique post-earthquake circumstances that may hamper the recovery of an asset and highlight the implications of its damage for the wider resilience of the network it belongs to. However, these predictions are currently conducted in isolation, neglecting the fact that any system in an urban environment is largely interconnected and significantly affected by the performance of neighbouring systems and

[8]https://www.onesanfrancisco.org

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regional infrastructure. For example, FEMA P-58 loss calculations fail to account for the significant post-earthquake downtime of a building (in any state of damage) that is surrounded by collapsed structures and has no functioning utility supplies. Thus, structure-specific repair time predictions need to be integrated within frameworks for modelling post-earthquake consequences that extend beyond the asset's footprint and are not exclusively related to engineering (physical) factors. They also need to be able to model the relationship between damage locality and recovery activities on the expected downtime and cost. One of the most promising related efforts to date has been the work of Cremen *et al.* [67], specifically in the context of post-earthquake business resilience. They established an analytical framework for modelling business recovery time that considers FEMA P-58 predictions of building recovery time as well as many other metrics, such as business relocation, disruption to suppliers, and utility downtimes. The results of this study highlight the importance of accounting for both engineering and non-engineering disruptions when modelling post-earthquake business interruption. However, the proposed framework is limited in its ability to predict business downtime, as it simplistically treats business recovery as a binary 'all-or-nothing' state.

For better-informed decision making on seismic resilience, structure-specific repair time predictions should be incorporated within comprehensive predictive frameworks for recovery that result in fully probabilistic projections of post-earthquake functionality trajectories. For example, a business interruption framework of this type should combine: *(a)* interdependent predictions of downtime in physical systems (*i.e.*, buildings, infrastructure, and critical utilities); *(b)* predictions of socio-economic disruptions, such as supply chain disruption and employee accessibility using proxy metrics from engineering, as well as quantitative tools from social science and economics; and *(c)* time-dependent measures taken by stakeholders to reduce downtime, such as relocation and the use of backup utilities, which could be robustly accounted for within a decision support system (Burton *et al.* 2018 [68]).

2.3 Resilience Quantification Considering Multiple Hazards

All systems are exposed to multiple hazards and/or cascading effects, such as multiple flood events during their lifetime, flood-earthquake, fire following earthquake, earthquake-induced tsunami, landslides and liquefaction, rainfall-induced landslides, ageing and earthquake events, or earthquake-aftershock events [69–74]. Combinations of these hazards usually exacerbates consequences, because they cause infrastructure performance to deteriorate faster, leading to loss of functionality and therefore spatiotemporally widespread effects.

However, nowadays, resilience evaluations commonly assume one single hazard, *e.g.*, the earthquake, ignoring preceding effects of other hazards, *e.g.*, scour and/or assets deterioration, ageing or other consequences prior to the seismic stressor [75]. Yet, these pre-earthquake stressors gradually reduce the earthquake resistance of assets and/or the functionality of networks, grids and lifelines, etc, hence leading to severe consequences impacting the world economies and societies (*e.g.*, [76,77]). There is currently no integrated framework that accounts for the nature and sequence of pre-earthquake hazards, their impacts, potential restoration strategies, and hence the quantification of earthquake resilience [74,78,79], with some exceptions that offer a holistic approach for quantified, resilience-based management of highway networks, yet, for a single hazard only [80,81].

To address the hazard gap, Argyroudis *et al.* [82] proposed a framework for the quantitative resilience assessment of critical infrastructure, which considers multiple hazard effects that may precede an earthquake excitation, the vulnerability of the critical infrastructure assets to hazard stressors, and the rapidity of the damage recovery, accounting for the temporal variability of the hazards. This resilience framework is illustrated in Figure 4 and enables loss and resilience evaluations of critical infrastructure assets under pre-earthquake hazard scenarios. The four steps of the framework are: step *(a)* is the quantification of single or multiple hazard scenarios on the basis of typical annual probabilities of exceedance of given intensity measures, step *(b) is* the definition of the fragility of an asset or the functionality loss of a network due to single hazards (1H) or multiple hazards (MHS), step *(c)* is the definition of the recovery models for the asset (capacity restoration) and the network (reinstatement of function); and step *(d)* is the convolution of steps *(b)* and *(c)* into resilience models. The assessment methodology accounts for the following common cases: *i)* the case where the asset is fully restored after the occurrence of Haz-1, *e.g.*, deterioration due to corrosion, and hence when Haz-2 strikes, *e.g.*, the earthquake, the asset and/or network are at their original full capacity; *ii)* the loss of functionality due to Haz-1 had been partially restored prior to Haz-2 occurrence; or *iii)* the defect of the asset or network due to Haz-1 remains and hence when Haz-2 occurs, the asset or network is/are already functioning at reduced capacity. This framework encapsulates redundancy and resourcefulness, *i.e.*, in *(b)* the asset and network robustness to hazard actions, based on realistic fragility curves or surfaces, which are available (in the case of earthquakes) for a wide variety of critical infrastructure assets (*e.g.*, Stefanidou and Kappos [83] for bridges, Argyroudis *et al.* [84] for tunnels, Masoomi *et al.* [85] and Burton *et al.* [86] for buildings), and in *(c)* the rapidity of the recovery after the occurrence of minor, moderate, major or complete damage, based on realistic reinstatement and restoration functions for infrastructure assets and networks (*e.g.*, Gidaris *et al.* [87], Mitoulis *et al.* [88], Mitoulis *et al.* [89]). It is worth noting that restoration/recovery could also aim at improving pre-event capacity/functionality, for instance through a *'build back better'* approach (*e.g.*, [90]).

However, while this framework proposes a rational methodology for multi-hazard resilience assessment of critical infrastructure assets and networks, several open issues must be addressed, some of which are now discussed. One of these issues is the temporal variability of different hazard effect occurrences, which is a crucial consideration for reliably assessing the resilience of assets and networks. It is important in the case of both: *(a)* abrupt hazard effects, *e.g.*, earthquakes, which define a new time reference for the functionality of the asset/network and *(b)* evolving hazard effects, *e.g.*, corrosion, which has different impacts on assets, depending on their age. The life-cycle of the asset and network is also a key piece of information for the assessment of resilience, as this determines the intensity of different hazard occurrences that affect the asset/network throughout its life and the rational combination of multiple relevant hazards. Hence, variations in the time of multiple hazard occurrences, the sequence of these occurrences, and the time between events may result in very different resilience quantifications for the same asset/network.

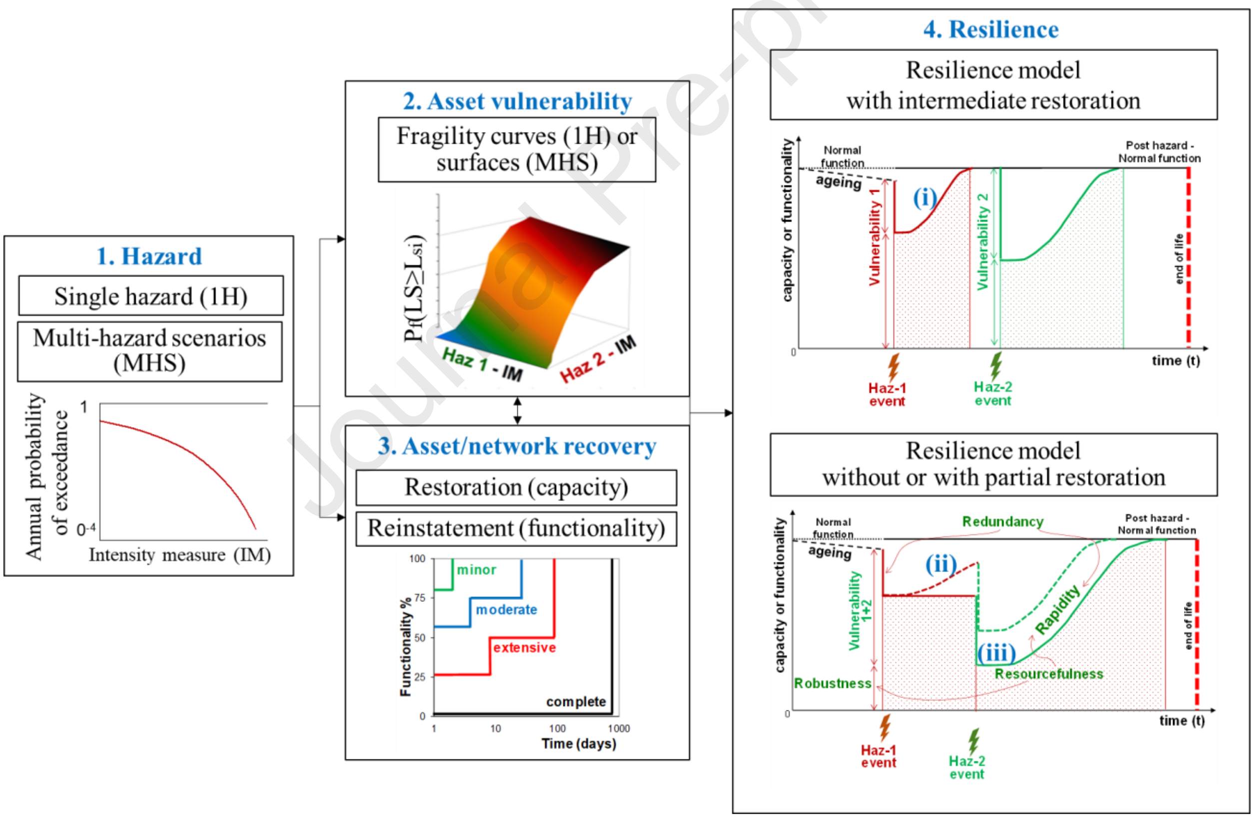

Figure 4. Multi-hazard resilience assessment framework (adapted from Argyroudis *et al.* [82]).

Moreover, there is no direct correlation between physical loss and loss of functionality in assets and networks. For example, a loss of capacity of a bridge after an earthquake of the order of 10% might lead to the complete loss of its functionality, *e.g.*, its use by vehicles and lorries may be prohibited. In addition, the decision to close railway or highway bridges after flash floods is - in some countries (*e.g.*, UK) - based on the occurrence of excessive inundation depths rather than any obvious damage. Thus, the correlation between the structural condition of the asset/network and its functionality is dependent on decisions made by consultants, stakeholders, and operators,

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which may also be influenced by political decisions, that align and adapt to the needs of the local communities. There is, therefore, a need for region-specific studies that provide better characterisations of the relationship between physical loss and loss of functionality, to enable more reliable estimates of the interdependencies between direct and indirect losses.

Another open issue relates to restoration measures. Retrofit strategies are typically assessed considering each hazard independently. However, approaches that improve system performance under one hazard may not be effective (or may even be detrimental) under other hazards. For example, strengthening of bridge piers with fibre-reinforced polymers (FRPs) to enhance capacity and increase flexural and/or shear strength will increase the earthquake resistance of the bridge, yet will provide minimal or no resistance to settlements as a result of scour.

Another challenge centres on the communication of resilience to stakeholders, which can include for example resilience metrics based on the cost of traffic detour and CO_2 emissions (see *e.g.*, [91]). The latter should define in the future how stakeholders perceive and implement resilience practices in their everyday problem-solving. There is an urgent need to communicate resilience among consultants, government and governmental bodies, local authorities, designers and assessors, communities and also to understand the related important role of the media. Operators tend to act toward suppressing rather than resolving problems, especially in emergency circumstances where siloed decision making is very frequent. Therefore, strong/didactic case studies on delivering resilience are necessary as guides to facing and resolving emergencies in a resilient manner.

3. PARAMETRIC INSURANCE FOR EARTHQUAKE HAZARDS

Insurance, in some form, dates back thousands of years to some of the earliest humans [92]. It is designed to provide private individuals and/or entities (*e.g.*, corporations, organisations, etc.) with asset protection from the adverse impacts of natural and/or man-made hazards through ceding (transferring) the entirety (or part) of the risk to an insurer. As human populations grow and expand into seismically active areas, their exposure and vulnerability to earthquake hazards is also increasing. As such, insurance organisations continue to broaden their risk-management tools and constantly look beyond traditional insurance products to accommodate a mounting number and type of risks.

As discussed above, catastrophic risks from natural hazards, such as the impact of ground shaking from earthquakes, present challenges for insurers due to limited knowledge on what controls the probability of extreme events and the need to holistically understand the potential drivers of loss. Traditional earthquake catastrophe insurance often relies on complex rating formulas (*i.e.*, statistical and mathematical calculations used to determine an insurance premium) based on the outputs from catastrophe models, with the objective of indemnifying the insured for actual losses incurred. These indemnity policies typically allocate payout(s) based on the losses realized for an event, the claims settlement process for which may take weeks, months or even years to resolve. Furthermore, traditional indemnity products for earthquakes usually include high deductibles (cost) and coverage limitations, which can result in low take-up rates (*e.g.*, [93]). According to OECD (2018)[9], earthquakes are one of the two least insured disaster perils (along with flood). Although there has been a recent improvement and good insurance penetration in several countries (*e.g.*, Turkey), approximately 85% of reported global earthquake losses since 2000 have been uninsured.

As an alternative to traditional earthquake insurance products, parametric or ‘index-based’ solutions remove the need to assess losses for the affected assets, by tying the payout decision and amount to near-real-time measurements of event parameters that are provided by an independent and unbiased third party such as a national geological survey. Broadly speaking, two types of earthquake parametric products are currently available: *(a)* first-generation ‘cat-in-a-box’ tools which trigger payments based on the meeting or exceedance of independently measurable fundamental parameters of the physical event, such as magnitude and hypocentral location (*e.g.*, [94,95]); and *(b)* second-generation triggers, which utilise recorded or inferred ground-shaking IMs (*e.g.*, peak ground accelerations, spectral accelerations at specific natural periods, macroseismic intensity, etc.) (*e.g.*, [96]) to define the exceedance of trigger thresholds.

[9] http://www.oecd.org/finance/Financial-Management-of-Earthquake-Risk.htm

Parametric insurance simplifies the traditional indemnity chain by removing the claims and loss adjustment processes, thus driving down the cost of the risk transfer solution while enabling rapid and transparent earthquake risk protection for individuals, corporations or even entire sovereign nations (*e.g.*, The Pacific Alliance Cat Bond [97]). However, parametric hedges carry significant basis risk, which can be defined as the potential difference between the parametric payout and the actual loss(es).

Multi-faceted, basis risk can be broken down into constituent parts. A few examples are as follows:

- Trigger error: flaws in the design of the trigger mechanism leading to a mismatch between the trigger(s) assigned to the loss proxy and the trigger(s) that cause actual loss (*e.g.*, using inappropriate models to determine the magnitude and hypocentral depth trigger thresholds);
- Instrument defects: error, malfunction or delay in providing or refining the magnitude and/or location of an event (*e.g.*, due to a sparse or faulty seismic network, damage caused by the earthquake, loss of power);
- Proximal cause: mismatch between the peril covered and the ultimate peril that causes the loss (*e.g.*, the recorded magnitude of an earthquake does not trigger a payout, but a subsequent tsunami causes actual loss);
- Modelling limitations: shortfalls in the input parameters to hazard models, such as the historical catalogue, stochastic event set, GMMs, etc. (as mentioned in the previous sections), which is quite common in low-income countries.

A key question in parametric insurance is how to minimise this risk [98,99]. It is often assumed that a stronger correlation between losses and local shaking intensity in second-generation products should make them superior to first-generation solutions. However, there is evidence to suggest that the uncertainties and modelling complexities in ground-motion IM estimates used in second-generation parametric indices are typically much larger than those affecting the main parameters of the event alone [100].

Two main trends have emerged from the most recent developments in general and parametric risk tools for insurance applications. Through added transparency, trust, and simplicity, Blockchain-based ‘smart contracts’ present a viable framework for new and more efficient parametric insurance solutions [101]. In addition, breakthroughs in artificial intelligence and other sophisticated analytical approaches are converging to allow the detection of patterns in data that would otherwise elude even the most expert risk modeller [102]. These features can be instrumental in the development of more accurate triggers and the inherent reduction of basis risk.

Blockchain is a distributed ledger technology in which transactions are recorded chronologically and publicly [103]. Although its first major application was related to a cryptocurrency, it has been increasingly associated with insurance, since it enables a friction-free, inexpensive and transparent transaction mechanism without the need for an intermediary, which is fundamental for providing transparent payouts [104]. ‘Smart contracts’ can further streamline this process, by codifying the relevant insurance policies necessary to expedite the payouts. Mismanagement of funds, high management costs and lack of transparency are perennial problems in indemnity-based insurance and parametric risk transfer solutions alike. However, blockchain-based parametric insurance is arguably faster, fairer, and cheaper. Once the premium is paid, the contract details are entered onto immutable blockchain software via a ‘smart contract’, ensuring that the payout is made when the pre-specified trigger parameters are met [104]. The instant and independent third-party verification of these parameters, coupled with the ability of the blockchain to consolidate data from several sources, can contribute to increased efficacy and accuracy, therefore improving affordability and reducing risk [105]. The use of blockchain in insurance is still maturing. The first blockchain settlement for a parametric insurance product was completed in 2017 by Solidum Partners[10], which consisted of a catastrophe bond for wind risk. Catastrophe bonds are fully collateralized instruments [92,106] that pay off on the occurrence of a specific trigger. Three types of triggering variables are traditionally used: *(a)* indemnity triggers, where payouts are based on the size of actual losses; *(b)* parametric triggers, where payouts are based on event parameters; or *(c)* hybrid triggers, which blend more than one trigger variable in a single bond. Parametric triggers, addressed in this section, are favoured by sponsors due to the flexibility and ease of payment they provide [67]. This transaction has become the first such securitization to be settled using a private blockchain – arguably the first to use this technology in a real-world application, rather than a proof-of-concept – paving the way for its use in parametric insurance against other perils, including earthquake.

[10] https://www.artemis.bm/news/first-blockchain-settlement-for-cat-bond-completed-by-solidum/

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Data also play an integral part in risk financing and decision making. Innovations that leverage big data can make catastrophe risk financing instruments quicker, more effective, more accessible and more reliable [102]. Prospective insurance and resilience applications of big data and machine learning include automated data collection, damage and impact forecasting, decision support for emergency response, post-event damage estimation and, in the case of parametric insurance, the design of more sophisticated triggers for parametric financial instruments. Despite the rising popularity of parametric risk transfer mechanisms, the number of scientific works discussing the development and definition of parametric triggers and their capacity to minimize basis risk remains limited [107]. Although a shift has been observed in recent years, the state-of-practice is arguably predominantly based on *ad hoc* approaches. The development of a trigger mechanism can be treated as a binary classification problem where one aims to maximize the number of 'true positive' and 'true negative' trigger outcomes, while minimizing the 'false positive' and 'false negative' cases [108]:

- True Positive: Payout is triggered, as intended;
- False Positive: Payout is triggered for an event that should not have resulted in a trigger by design;
- True Negative: Payout is not triggered, as intended;
- False Negative: Payout is not triggered for an event that should have resulted in a trigger by design.

The use of machine learning methods can offer several advantages in this framework. They may be able to find relationships between event parameters and corresponding event losses that would otherwise elude *ad-hoc* and 'traditional' statistical approaches. As an example, Calvet *et al.* [107] have shown that the added 'skill' of non-linear and non-parametric techniques (*i.e.*, nearest neighbours classifier, classification trees, neural networks and support-vector machines) consistently outperform less sophisticated statistical tools in terms of accuracy (*i.e.*, the mechanism's ability to trigger when it should, and to not trigger when it should not) sensitivity (which relates to how often the mechanism triggers when it should trigger) and specificity (which relates to how often the mechanism does not trigger when it should not). With the added capacity of combining and analysing live data feeds and existing data sets in real time to determine trigger threshold values, big data and machine learning-based approaches have the potential to decisively contribute to a reduction of basis risk. At the same time, increased reliance on computer-driven tools introduces new risks, including errors in data processing and misinterpretation of data inputs. Equally, the outcomes of even the most sophisticated algorithms are only as good as the input data. Any systemic bias or exclusion in data inputs will inevitably lead to biased results unless otherwise accounted for [102].

4. EARTHQUAKE EARLY WARNING

Earthquake early warning (EEW) is becoming an increasingly popular real-time DRR strategy in urban settings worldwide, *e.g.*, in California, Japan, Mexico and Romania [109]. EEW systems consist of sensors, methods and models for computing the seismological characteristics (magnitude, location, and/or shaking) of incoming earthquakes from early seismic signals (*e.g.*, [110]). These preliminary event data are then used to determine whether an alert should notify relevant stakeholders (*e.g.*, civil protection authorities) to take important risk-mitigation actions (*i.e.*., protective measures) before strong shaking occurs at target sites. Examples of the rapid protective measures that can be facilitated by EEW include the 'drop, cover, and hold' manoeuvre by individuals (to avoid injuries), the shutting down of gas pipelines (to prevent fires), and the stopping/slowing down of trains (to avoid derailments). The effectiveness of an EEW system in lowering earthquake-induced risks largely depends on: *(a)* the accuracy of the seismological parameter estimates computed by the underlying EEW algorithm (*e.g.*, [111]); *(b)* the speed at which the system issues an alert (*e.g.*, [112]); *(c)* the proximity of the target site to the earthquake source (which determines the amount of warning time available) [113]; *(d)* the physical vulnerability of the structures/infrastructure for which the risk-mitigation actions are designed; and *(e)* end-user support for the system (*e.g.*, [114]). In some countries (*e.g.*, Japan and Mexico), EEW deployment has been driven by the occurrence of major earthquake disasters, without any specific economic justification being required. In other cases (*i.e.*, California), delays to EEW installation were partly attributable to the lack of cost-effectiveness for mitigating industrial losses. However, recent studies [115,116] have demonstrated that the benefits of EEW clearly justify its operational cost in the state.

From a technical perspective, modern advancements in EEW applications have largely concentrated on the seismological aspects of systems [117]. For example, notable recent EEW research efforts have focused on developing innovative finite-fault approaches for computing magnitude that result in significantly better estimates of the size of an ongoing event than previously proposed empirical models [111]. Enhancing the timeliness of issued alerts has also been addressed in some related studies, which have strived to reduce the uncertainties in the seismological outputs of rapid single-station EEW algorithms (*e.g.*, [118,119]). On the other hand, current methods for end-user-decision-making related to the issuing of alerts in EEW systems are relatively simplistic and do not explicitly account for the end-to-end risk-mitigation potential of triggered actions [117]. For example, alerts are often simply triggered when the estimated value of a ground-shaking/ intensity metric exceeds a predefined threshold, ignoring ingredients *(d)* and *(e)* of an effective EEW system. This may result in an underestimation of false and missed alerts [117]. False alerts can lead to costly disruptions in industrial settings [120], while missed alerts are potentially deadly.

To overcome current decision-making limitations in EEW, Cremen and Galasso [121] recently developed a next-generation engineering-oriented decision-support system for risk-informed EEW (Figure 5). This methodology leverages the performance-based earthquake early warning framework proposed by Iervolino [122] to translate uncertain seismological parameters to damage and loss metrics, using application-specific fragility functions and damage-to-loss models. It also explicitly accounts for end-user preferences, through the use of multi-criteria decisional tools. The methodology of Cremen and Galasso was originally designed for application to individual buildings, although it has been successfully adapted for interdependent losses associated with network-based infrastructure [123]. In this latter case, the proposed decision-support system is applied to the Southern Italian port of Gioia Tauro, one of the most important hubs for container traffic in the Mediterranean Sea, located within the region characterized by Italy's highest seismic hazard. The study uses a simulation-based approach that considers several layers of interdependencies among vulnerable elements to capture the multicomponent interconnected nature of the port's performance. These analyses enable the quantification of the consequences of simple, automated EEW mitigation actions, (*e.g.*, activating sirens to evacuate buildings or shutting down electricity systems to avoid damage/minimize disruption). Remaining challenges for EEW decision-making include explicitly accounting for the uncertain amount of available warning time and developing a risk-driven approach that is suitable for application to large portfolios of assets (*e.g.*, [124]).

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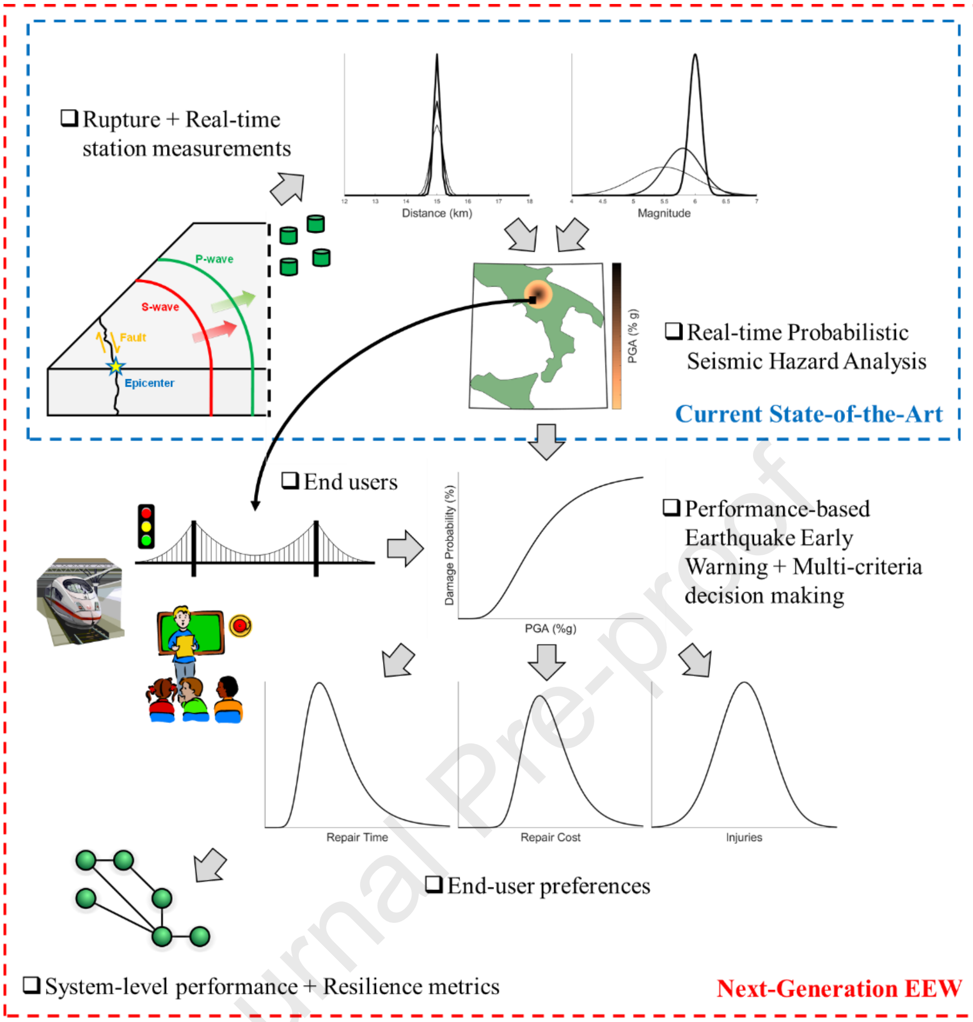

Figure 5. Conceptual overview of the next-generation EEW decision-making methodology developed in Cremen and Galasso [121] (adapted from Cremen and Galasso [117]).

From a socio-organizational perspective, a recent review by Velazquez *et al.* [125] has uncovered diverse opinions about the information that needs to be included in EEW alerts, to maximise their effectiveness. Some literature (*e.g.*, [126,127]) claims that "simple warnings", which do not provide available warning times or reveal the characteristics of the incoming ground shaking, are typically not favoured by end users (*e.g.*, general public). In particular, properly trained individuals appear to prefer knowing the available warning time, to help them best decide the optimal protection action to undertake during ground shaking. Similarly, some studies conclude that organizations need contextual information on the event in alerts, to facilitate the activation of prudent/cautious mitigation actions (*e.g.*, [120,128]). However, other literature argues that simple warning messages may be enough and more appropriate, as they facilitate direct actions such as 'drop, cover, and hold', and the processing of many additional details can lead to delays in responses (*e.g.*, [109,129]). Velzaquez *et al.* [125] also identified that the effectiveness of EEW can be negatively impacted by a lack of coordination between official bodies that provide warnings and those organisations that can benefit from them. This problem is particularly evident in Mexico, where there is no formal strategy for identifying critical assets (*e.g.*, schools, lifelines etc.) that should receive EEW alerts [130]. A complete summary of the socio-organisational challenges/considerations for implementing EEW is provided in Figure 6.

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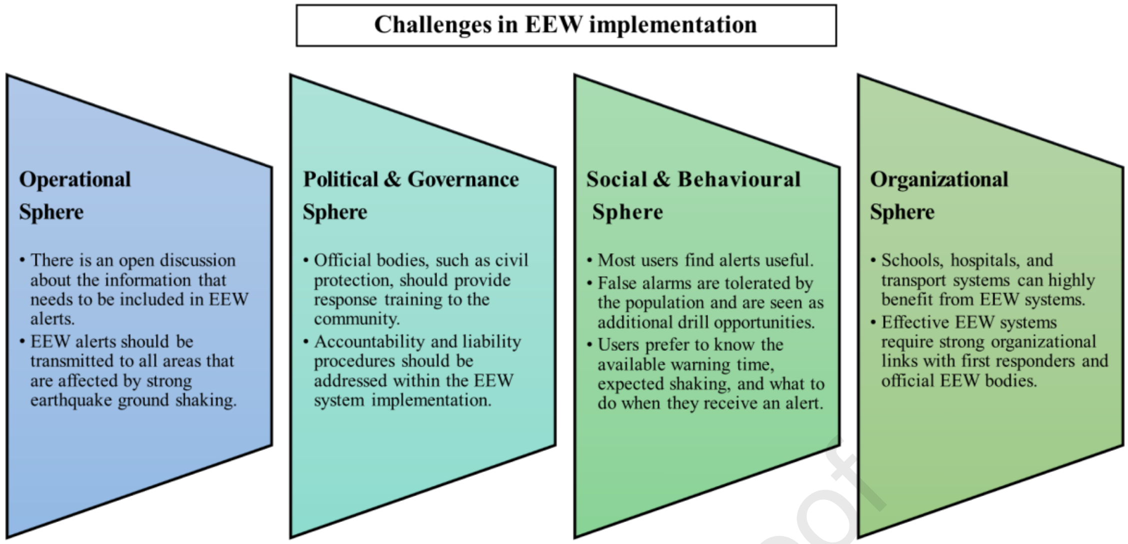

Figure 6. Socio-organisations challenges and considerations for implementing EEW (adapted from Velazquez *et al.* [125]).

5. SUPPLEMENTAL DAMPING & ISOLATION

A different 'family' of earthquake-related DRR strategies aims to enhance structural and infrastructural safety and resilience through the implementation of *'hard'* technical measures such as the use of novel structural systems and materials, innovative structural devices, sensors, etc, for both new and existing structures and infrastructures.

Traditional seismic design methods, suggested by most current codes and guidelines (*e.g.*, [131–138]) and conventionally applied worldwide, are based on energy dissipation related to structural and foundation damage, hence leading to large direct and indirect losses in extreme events. This strongly affects the overall resilience of affected communities, especially when the damaged structures include strategic facilities such as hospitals, fire stations, etc that must remain operational in the aftermath of a damaging earthquake.

In contrast, innovative technologies based on passive control, isolation, or energy dissipation systems, for example, offer the opportunity to preserve both structural and non-structural components from damage, hence contributing to the enhancement of resilience (*e.g.*, [139–149]). Nowadays the application of these systems is mature and is becoming popular in many earthquake prone regions. An overview of the various worldwide applications of these earthquake protection strategies is provided in Martelli *et al.* [150].

However, while design strategies are well consolidated in the case of traditional solutions (*e.g.*, capacity design), and have demonstrated their capabilities with respect to exceptional events, additional investigations are required for seismic isolation and supplemental damping systems. More precisely, traditional structures are typically prone to suffer damage, but they show a satisfactory robustness (*i.e.*, in this context 'robustness' denotes the capability of the system to safely withstand loading intensities higher than the designed one) deriving from redundant static schemes and ductile properties of the materials. Conversely, systems involving the use of innovative devices are very efficient in reducing damage and have a reliable response thanks to quality control tests, but often show a brittle behaviour that may strongly reduce global robustness in the case of extreme and rare seismic actions. Furthermore, device collapse modalities are not sufficiently investigated and consequently, models adequately describing complete device response (*i.e.*, up to failure) are not still available in many cases.

A short overview of some open issues related to the use of these strategies is now presented, with techniques grouped in two categories: *(a)* seismic isolation; and *(b)* damping devices.

5.1 Isolation Systems

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Seismic isolation aims to uncouple the motion of the structure from the ground shaking and thereby reduce structural forces, accelerations and deformations of buildings under strong earthquakes [151]. These innovative devices are nowadays widely used for new construction in earthquake prone regions [150].

Several types of isolator have been developed, including rubber bearings, sliding devices and friction pendulum isolation systems, among others, each of them is characterised by some advantages (*e.g.,* dissipation capacities, self-centring behaviour) and disadvantages (*e.g.,* high operating costs, high maintenance requirements, reduced effectiveness over time). However, apart from the specific aspects that need investigation for each different typology, there are still some common open issues.

These devices are produced in quality-controlled processes and it has been demonstrated that the expected variability of device properties generally does not notably influence system response [152,153]. However, the isolation system works well only if the superstructure is sufficiently rigid and elastic limits are not exceeded. Furthermore, isolation devices often show a brittle failure, and this may trigger failure of the whole system [153–156].

Code-conforming design procedures check the seismic response at special hazard levels only and the actual reliability level relies on an adequate choice of safety coefficients. As an example, European codes (*i.e.,* EN 1998-1 [131], EN 15129 [157]) require the design to be developed with reference to a conventional seismic action that has a mean annual frequency (MAF) of exceedance equal to 2.1×10^{-3} (*i.e.,* Life Safety Limit State) and some coefficients are used to guarantee a probability of failure lower than 1×10^{-4} per year [158]. The values of these coefficients are well constrained in the case of traditional solutions, but are still a matter of discussion and require deeper insights for seismic isolation systems [156,159]. This is a very critical point because traditional solutions are usually based on redundant and ductile systems, *e.g.,* reinforced concrete (RC) or steel frames, which have the capability to withstand exceptional events, while seismically isolated structures may show brittle failures and may be prone to disproportionate consequences under exceptional actions. Hence, seismic isolation shows promise in providing resilience, thanks to its ability to limit damage, but it may suffer from a lack of robustness that may reduce its benefits under extreme earthquake events.

In order to investigate this aspect, recent on-going studies are focused on the response of structures exposed to extreme loadings and failure modalities that may occur either in the bearings or in the superstructure (*e.g.,* Ragni *et al.* [153] and Tubaldi *et al.* [160] for elastomeric bearings, Kitayama and Costantinou [156] for friction bearings). For demonstrative purposes, some results concerning the response of an RC building isolated by High Damping Rubber Bearings (HDRB) [153] and designed according to Italian codes [132] (almost identical to the Eurocode) are now summarized. Figure 7(a) provides a general view of the case study building, and a qualitative representation of the cyclic response of the HDRBs is shown in Figure 7(b). Figure 7(c) shows the MAF, $v_{IM}(im)$, of exceedance of the IM values considered in the analyses for the site of interest. The red point in Figure 7(c) denotes the intensity level and corresponding MAF of exceedance considered for the design (*i.e.,* Ultimate Limit State). Figure 7(d) displays the system failures (*i.e.,* buckling of the isolators and failure in the superstructure) observed when 20 accelerograms are investigated for each IM level. It is worth observing that, although the system performs well at the design IM level, some failures occur for intensity levels characterized by a MAF of exceedance larger than the usual target failure rate (1×10^{-4} 1/yrs) and they may involve either the isolation system or the superstructure. Differently from traditional systems, where seismic intensities over the design value usually produces local failures and the global failure only occurs for intensity level far from the design value, in the case of isolation systems the bearing devices almost fail all at once, producing a cliff edge effect in the fragility curve, as already observed in [154], and the probability of failure suddenly move from low values to values close to 1 at a critical value of intensity.

However, definitive conclusions about robustness and reliability of isolation systems require further investigations in specific topics; there is still a lack of adequate models for the response of supporting devices, and considerations of bidirectional response and varying collapse modalities are currently insufficient. Regarding HDRB, complex non-linear phenomena were separately investigated (*e.g.,* cavitation under traction, softening under cyclic shear load, stiffness reduction due to axial load) but their interaction is not fully understood and experimental tests on failure modalities are not available. Friction-based isolation systems suffer from similar challenges; interaction between the friction coefficient and other quantities, such as temperature, velocity and pressure, are not fully understood and the uncertainties considered are strictly related to the sliding path followed during the seismic event [161]. Behaviour beyond service conditions and failure modalities also requires further investigation.

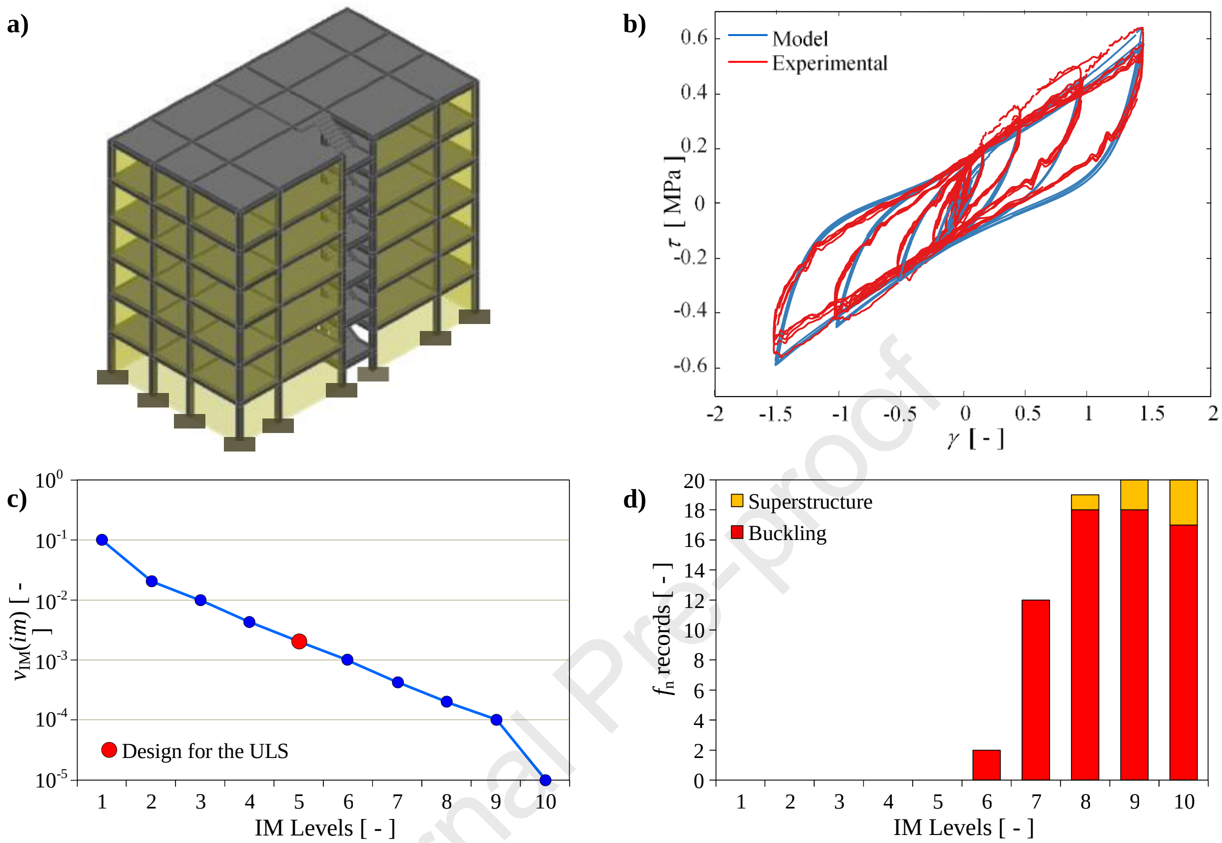

Figure 7. (a) General view of the case study; (b) cyclic response of HDRB; (c) mean annual frequency (MAF) of exceedance of intensity measure (IM); (d) system failure (adapted from Ragni *et al.* [153]).

5.2 Damping Devices

Supplemental dampers can be introduced within the structure to absorb seismic input energy and convert it to heat, hence reducing both displacement and acceleration demands on the structure. Damping devices are usually classified under two categories: *(a)* displacement-dependent devices and *(b)* velocity-dependent devices. Metallic and friction dampers belong to the first category, while the second category includes visco-elastic and viscous fluid dampers. A third, less conventional category accounts for dynamic vibration absorbers and inertial dampers, where the seismic response is controlled by adding inertia to structures.

5.2.1 Displacement-Dependent Devices

This large family of supplemental damping devices is based on the development of a hysteretic behaviour that is related to the plastic deformation of ductile materials or to the frictions between two surfaces in contact (*e.g.*, [139,140,142–146]). Currently, one of the most widely used displacement-dependent devices is represented by buckling-restrained brace (BRBs) (*e.g.*, [162]), also known as unbounded braces, and often employed as diagonal braces for new structures and for the seismic retrofitting of existing frames. A typical layout of BRBs is provided in Figure 8(a), which shows the unbonded metal core (*i.e.*, the yielding component), the filler material (*i.e.*, mortar) and the external metallic case that provides confinement to the filler. The external components provide buckling resistance to the core that resists the axial stress, and, as buckling is prevented, the BRB's core can develop axial yielding in compression in addition to that in tension, ensuring an almost symmetric hysteretic behaviour as shown in Figure 8(b) (*i.e.*, the compressive strength is almost 15-20% greater than tensile resistance).

The use of these braces enhances the stiffness and strength of the system under horizontal loads and provides large and stable energy dissipation capacity. Figure 9 provides the typical cyclic ‘base shear - roof displacement’ response of a RC building structure retrofitted with BRBs positioned along the perimeter frames. The contributions of the diagonal BRBs and the response of the existing structure are plotted separately to demonstrate that, if properly designed, the as-built RC system can remain in the elastic range while the energy dissipation is primarily generated by the added dampers thus promoting structural resilience. This example shows that the use of BRBs is a highly efficient method that can be a viable and versatile option for use in retrofitting existing vulnerable structures.

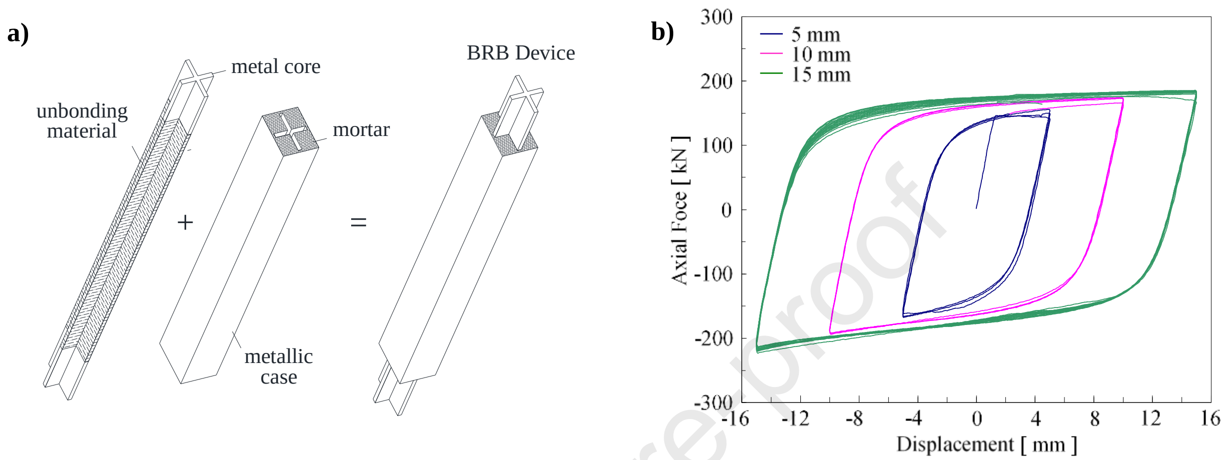

Figure 8. Typical buckling-restrained brace (BRBs). (a) Layout and (b) response to cyclic loading at increasing amplitudes.

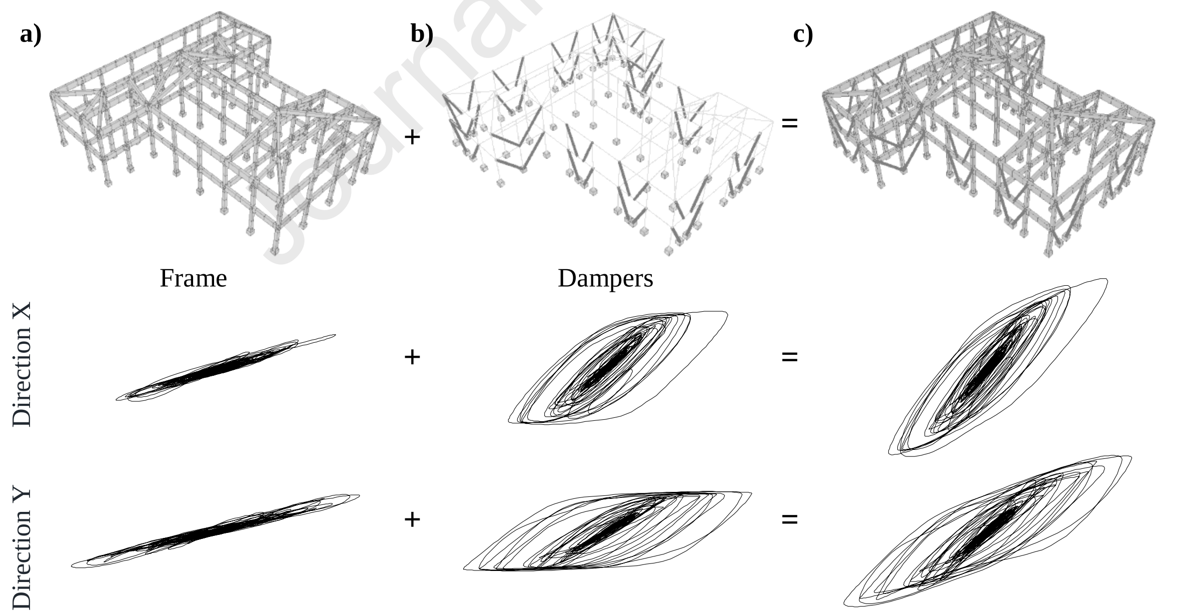

Figure 9. Cyclic response and energy dissipation for: (a) the existing structure; (b) the buckling-restrained braces (BRBs); (c) the structure with BRBs (adapted from Di Sarno and Manfredi [163]).

The large and stable energy dissipation capacity of BRBs has been demonstrated in many experimental campaigns (*e.g.*, [164–168]) that advanced understanding of both the monotonic and cyclic response of these devices.

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It has been observed that the cyclic response of BRBs is characterised by isotropic as well as kinematic hardening (*e.g.,* [169]), where large ductility demand values are reached without a significant increase of force, due to a low post-yielding stiffness. While the low post-yielding stiffness enables the development of large hysteretic loops, it causes large sensitivity of the seismic response to brace over-strength distributions that could result in inter-storey drift concentration (*e.g.,* [170]) and large residual inter-storey drifts. To improve system robustness, the design of dissipative braces should account for the mechanical response of the existing structure and the horizontal strength and stiffness should be realistically determined to optimize the energy dissipation of the BRBs. To address this problem, some studies focused on the development of design methods for the optimal distribution of device properties within the frames (*e.g.,* [171,172]) and considered the influence of Moment Resisting Frames (MRFs) working in parallel with the BRB system (*e.g.,* [173,174]). Further studies on this topic are still required.

In addition, experimental tests demonstrated the susceptibility of BRBs to low-cycle fatigue fracture caused by limited cumulative ductility capacity (*e.g.,* [175]). Large residual drifts and accumulation of ductility demand in the BRBs due to an earthquake may jeopardize seismic performance under successive seismic events, *i.e.,* successive mainshocks or aftershocks within the same seismic sequence. Some studies on improving system robustness are currently on-going, which provide insights on relevant design methods (*e.g.,* [176,177]). Among others, Morfuni *et al.* [176] investigated the influence of repeated earthquakes on the ductility demand accumulation of BRB devices. Figure 10(a) shows the fragility curves developed for a case study steel frame with BRBs, where the considered Engineering Demand Parameter (EDP) is the cumulative ductility demand and the effect of mainshocks with increasing intensities (*i.e.,* MS_1 smallest intensity and MS_4 highest intensity) is analysed. The results show that more severe mainshocks induce increasing levels of initial damage that are associated with a higher probability of collapse, while BRBs that sustained a mainshock with a small intensity are likely to sustain a subsequent earthquake without a significant increase in the probability of failure. Thus, replacement of BRBs might be recommended in the presence of strong mainshock events. This is a particularly challenging issue, considering that device failures are generally brittle leading to a lack of system robustness, yet it is typically difficult to identify damaged devices after a seismic event. Very few studies have addressed this issue and additional research is required.

Additional open issues relate to the effect of BRB property uncertainties on the reliability of the system. In fact, while the effect of some uncertainties, such as the ground motion record-to-record variability, is often investigated (*e.g.,* [174]), only a deterministic description of the dampers' properties is usually considered. Previous studies (*e.g.,* [178,179]) have shown that the effect of model parameter uncertainty is usually negligible with respect to the record-to-record variability. However, this may not be the case in structures equipped with dampers, since the seismic response is significantly dependent on the properties of a small number of devices. This aspect is also highlighted by several design codes, *e.g.,* ASCE/SEI 7-16 [133] and EN 15129 [157], which mandate the consideration of possible variations in device properties with respect to nominal ones. BRBs are typically manufactured and successively assessed by qualification control tests based on tolerance limits established by seismic and qualification codes (*e.g.,* [132,134,157]). Some device-to-device variation is possible within the tolerance limits, which could significantly affect the seismic performance of the structure. Very few studies have been conducted on this topic for hysteretic dampers (*e.g.,* [180,181]). Related research for viscous dampers is slightly more advanced and is discussed in the following Section.

Among others, Kotoky *et al.* [180] and Freddi *et al.* [181] investigated the variability in the seismic performance of a BRB-retrofitted case study RC frame, by considering the device-to-device uncertainty facilitated by the tolerance limits used in device qualification control tests. All possible combinations of acceptable device deviations from nominal values were considered and Figure 10(b) shows the resulting fragility curve bands across each combination. Fragility curves are reported for all the damage states (*i.e.,* Slight, Moderate, Extensive and Complete) and a significant variation in retrofit performance due to BRB parameter uncertainty is observed, highlighting the need for additional research in this direction.

Friction devices (FDs) (*e.g.,* [182,183]) are another type of displacement-dependent device. The use of these devices has been widely investigated and, among others, one of their interesting applications is to facilitate damage-free beam-to-column connections in MRFs. Grigorian *et al.* [184] pioneered a first FD in beam-to-column connection, and successive research studies and practical applications have carried out to investigate several configurations for this connection typology (*e.g.,* [141,148,149,185]). FDs are usually introduced at flange level with flange plates, and a web plate with elongated holes that permits sliding of a friction interface. This strategy has been widely investigated in recent years, demonstrating the efficiency of this solution both numerically and experimentally. However, some challenges still need to be addressed. The durability of the friction dampers is an important topic requiring investigation, which concerns both the potential loss of initial bolt pretension and corrosion phenomena. Some related preliminary tests have been already conducted, but new studies are required to provide final conclusions where contaminants (*e.g.*, SO2 or CO), which may potentially impair the use of the friction devices, are also present. A further research challenge is the creep behaviour or the potential loss of bolt preload as a result of vibration phenomena (*e.g.*, [186,187]). Additional research is also required to investigate the effect of velocity on the friction coefficient value; only a few studies have focused on this topic to date (*e.g.*,[188,189]).

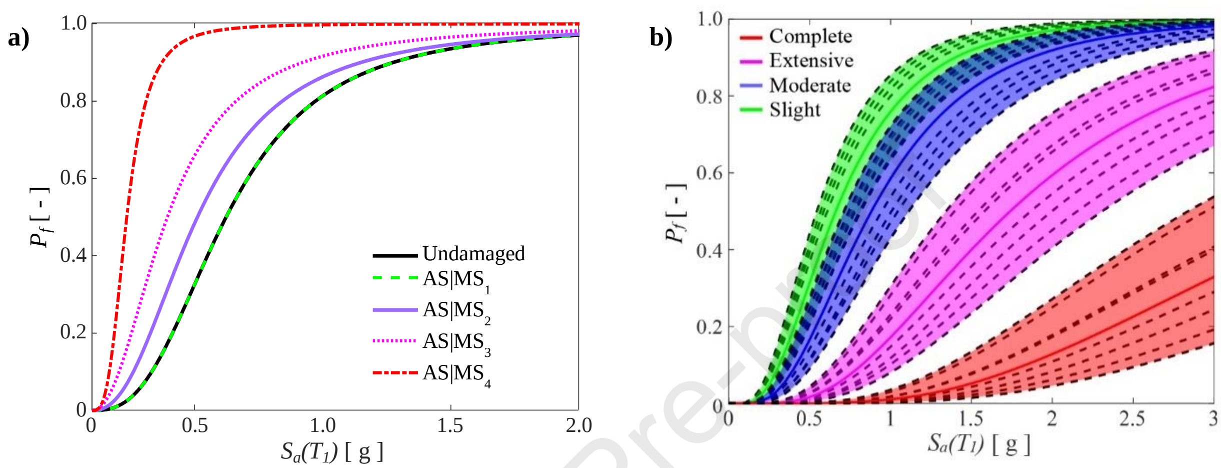

Figure 10. (a) BRB cumulative ductility-based fragility curves for the collapse limit state, conditioned on the level of damage induced by mainshocks with increasing intensities (adapted from Morfuni *et al.* [176]); (b) Seismic fragility curves, accounting for BRB parameter uncertainties related to tolerance limits used in device qualification control tests, for Slight (S), Moderate (M), Extensive (E) and Complete (C) damage states (adapted from Kotoky *et al.* [180]).

5.2.2 Velocity-Dependent Devices

Dampers for which the response depends on velocity are a large family of dissipative devices that includes purely viscous dampers, devices based on visco-elastic materials, and more complex systems combining elastic and viscous components. The dissipated energy permits the reduction of forces and deformations in the structure, controlling the safety level under 'rare' (*i.e.*, high intensity) seismic events, as well as limiting the damage under low to medium seismic intensities (*e.g.*, [190–192]).

Generally, velocity-dependent dampers work in parallel with traditional structural systems and both of them contribute to the overall performance, so the resulting solution is very flexible and can be applied to solve a wide range of seismic performance problems. However, device failures are generally brittle, and this may lead to a lack of robustness of the overall system. Further investigations are required to define more effective design procedures and calibrate safety factors that can provide the same safety level for different configurations and dampers with varying properties (*i.e.*, linear/non-linear). Failure modes of dampers are also not fully understood, and related studies are on-going [193]. Furthermore, the seismic reliability of these systems, usually measured by the annual probability of failure, is also strongly influenced by the real response properties of the devices. There is a close relation between expected response and accepted tolerance in the production process [194,195]. Finally, viscous dampers cover a wide class of devices, whose behaviour spans from linear to non-linear, and the overall performance can notably vary depending on the intensity level of the input action [196,197].

This point is demonstrated in Scozzese *et al.* [198] while investigating a case-study three-storey steel MRF equipped with viscous dampers where the failure of dampers has been modelled according to Miyamoto *et al.* [193]. The MRF has been modelled by a simplified approach, assuming rigid beam-to-column connections and without modelling possible local failure, while a detailed model has been used for the device (to describe the dampers'

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failure due to the attainment of the maximum stroke and force capacities). The results of the study are shown in Figure 11. Figure 11(a) shows the response, measured in terms of maximum inter-storey drift (IDR) versus IM, for the case of a bare frame (black solid line), and for the case of a frame with viscous dampers, which were designed without considering any amplification factor for the values of the stroke and the forces determined according to the ultimate limit state seismic intensity level. The red dashed line and the solid blue line correspond to the response obtained by neglecting or considering the device failure, respectively. Viscous dampers notably reduce the IDR and, more generally, the seismic demand for low IM levels (*i.e.*, below that considered in design). However, it is evident that the beneficial effect of the viscous dampers is vanished for ‘rare’ seismic actions (*i.e.*, with intensity twice that of the design), due to device failure. Figure 11(b) illustrates the consequences of damper design on the seismic reliability of the system, expressed in terms of MAF of exceedance of different IDR levels. The dampers are designed by considering a seismic action with a MAF of exceedance equal to 2×10^{-3} (black dotted line) and structural collapse should be limited to MAF of exceedance lower than 2×10^{-4} [158]. The black solid line and the red dashed line show the IDR demand hazard curve obtained respectively for the bare frame and for the frame with added dampers, disregarding device failures. Plotted in the same figure is the demand hazard curve obtained for the case with added dampers that are designed considering an amplification factor of 1.5 for the design strokes and forces. It is evident that damper failure may significantly reduce reliability, and that adequate amplification factors for the dampers' response must be employed to ensure that the system structural safety is not jeopardised.

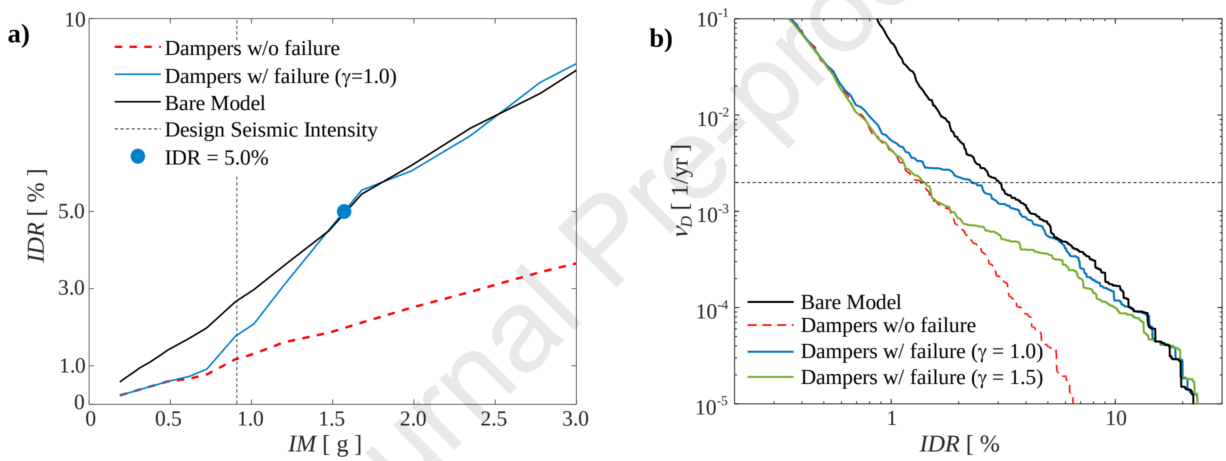

Figure 11. Three-storey steel frame with linear viscous dampers: (a) Inter-storey drift (IDR) for increasing seismic action; (b) IDR demand hazard curve for the bare frame and the frame with dampers designed according to various criteria (adapted from Scozzese *et al.* [198]).

5.2.3 Arrangement of Devices within the Structure

The devices described in previous sections can be arranged in many different ways within newly designed and existing buildings. Device arrangement is a particularly important consideration for the retrofitting of existing structures, where device integration based on conventional configurations often leads to long business interruption with consequent high indirect losses. Long business interruption is one of the main factors preventing widespread application of seismic retrofitting measures in many countries worldwide. Several innovative configurations have been investigated in the last few years to overcome this issue, *e.g.,* devices utilized within an ‘exo-skeleton’ as shown in Figure 12, or connecting the structure to ‘external dissipative bracings’ as shown in Figure 13 (*e.g.,* [199–202]).

In an ‘exo-skeleton’, the dissipative devices are introduced within diagonals applied along the exterior frames of the structure, as illustrated in Figure 12. The dissipative braces are connected to the existing vulnerable framed systems, which can be forced to remain in the elastic range under seismic loads. From a mechanical standpoint, a parallel system is formed between the framed structure and the external braced system. Thus, the global response of the structural system can be assumed as the sum of the elastic frame (primary structural system) and the system formed by the diagonal braces (secondary system). The primary system is capable of withstanding vertical loads and

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behaves elastically under earthquake loads. The secondary system includes the dissipative members and is designed to dissipate the seismic input energy.

Numerous applications of either BRBs applied on the external frames of existing seismically vulnerable buildings or 'exo-skeleton' have been carried out in the aftermath of recent earthquakes in Italy, especially for school and hospital buildings, *e.g.*, Di Sarno and Manfredi [163]. These applications are also sufficient to limit excessive seismic demands on the foundations, thus reducing the overall cost of structural interventions.

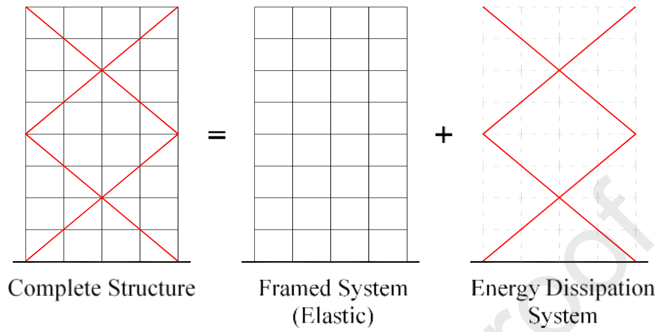

Figure 12. Typical framed structures with dissipative diagonal braces placed externally (exo-skeleton).

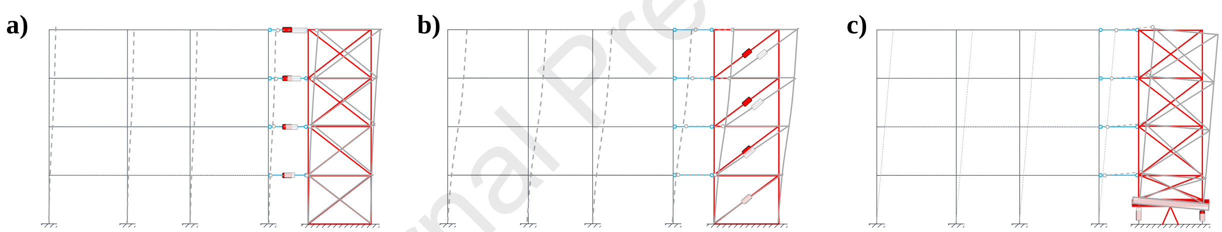

Figure 13. Illustration of three categories of external dissipative systems: (a) dampers placed horizontally at the storey level between the frame and an external stiff contrasting structure; (b) dampers incorporated within a new shear deformable structure; (c) pinned rocking bracing with dampers located at the base.

'External dissipative bracings' are based on the same concepts; they are generally concentrated on the same portion of the building, avoiding a full envelopment of the structure. External systems provide a very flexible family of solutions and Figure 13 illustrates some possible configurations that may be used in existing buildings with different strength and stiffness characteristics. Possible configurations can be grouped into three main categories, characterized by substantially different kinematic behaviours. In the first arrangement (Figure 13(a)), the dampers are placed horizontally at floor level, and the links are activated by the relative displacements between the frame and the external structure. An alternative arrangement consists of coupling the frame with an external shear deformable bracing structure (Figure 13(b)). The new and existing structures are connected at the storey level and the dissipative devices, incorporated in the diagonal braces of the new structure, are activated by the relative displacements between adjacent floors, as in the more traditional case of dissipative braces placed within the existing structure. A third arrangement, denoted as 'dissipative tower', consists of external stiff bracings linked to the frame at the storey level and connected at the foundations by a hinge (Figure 13(c)). The energy dissipation is provided by dampers placed at the external frame base and activated by rocking motion.

Connections between the existing frame and the 'exo-skeleton' or 'external bracing' are an important aspect (among others) that still require further investigation. The failure of these connections may impair the global performance of the retrofit. Moreover, it is important to highlight that the influence of ageing - often relevant in existing structures that need additional local strengthening interventions - should also be considered when assessing the adequacy of the connections. How to properly account for the aging of existing structures is still an open issue and several research studies are currently investigating this topic.

Interaction of the existing frame with the existing masonry infills - which could significantly contribute to the lateral stiffness and strength of the primary structure - also requires further consideration. This interaction already exists for conventional configurations; however, proper consideration of the effects of masonry infills is particularly important when innovative dissipative systems are introduced, since they may impair the robustness of the intervention.

5.2.4 Dynamic Vibration Absorbers and Inertial Dampers

Further to, and in combination with, the previously discussed approaches (*i.e.*, base isolation and supplemental damping devices), the suppression of earthquake-induced structural deflections can be achieved by adding inertia to structures. This approach is founded on structural vibration control principles and is technologically implemented by equipping structures with one (or more) of the following types of devices *(a)* dynamic vibration absorbers (DVAs); *(b)* inerters; and *(c)* inertial dampers.

The DVA, for which the main example is the tuned mass damper (TMD), was historically the first passive structural vibration control strategy [203]. It has been extensively researched and has wide applications in the vibration suppression of dynamically excited structures and structural components due to its simplicity (*e.g.*, [204]). An ideal mechanical representation of a TMD is shown in the top-most inlet of Figure 14(a). It comprises a free-to-oscillate (secondary) mass attached to the primary structure (*e.g.*, a multi-storey building) via a spring element in parallel to a dashpot (*e.g.*, viscous damper). For a given secondary mass (m_d) the TMD stiffness (k_d) is 'tuned' to resonate to a single most dominant (detrimental) structural vibration mode. In this manner, significant kinetic energy is transferred from the primary structure to the secondary mass (*e.g.*, amplitude of y displacement in Figure 14(a) is much larger than x_i floor deflections) and, ultimately, dissipated at the dashpot. For regular building structures, TMDs are placed towards the top floor to suppress the fundamental mode shape (*e.g.*, [205]), while for base-isolated structures TMDs may be placed at the isolation layer (basement/ground floor) to mitigate the lateral deflection demands of the isolators (*e.g.*, [206]).

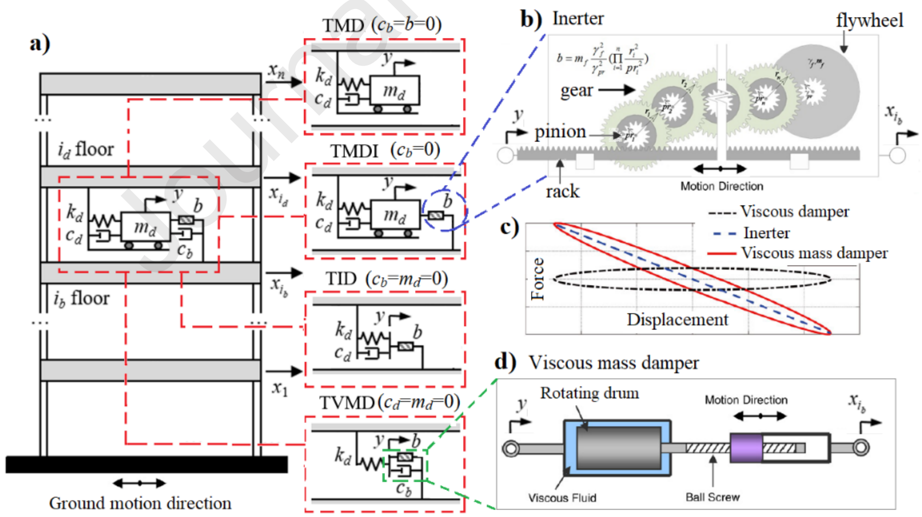

Figure 14. (a) Idealized mechanical representations of various dynamic vibration absorbers (DVAs), (b) Idealized rack and pinion flywheel-based inerter with gearing (adapted from Taflanidis *et al.* [207]), (c) Force-deformation relationships of inertial dampers, (d) Idealized viscous mass damper with ball-screw inerter mechanism.

Most practical TMD implementations for top-floor building placement are pendulum-like, in which the secondary mass, consisting of concrete blocks (*e.g.*, [208]), or steel plates/spheres (*e.g.*, [209]), is hung from strengthened beam elements and acts along two horizontal perpendicular axes or is axisymmetric. Regardless of the nature of the additive mass, DVA motion control efficacy, and robustness to detuning, depends on its inertia [210]. To this end, enabling a large secondary mass - subject to structural and architectural constraints - becomes the critical consideration for satisfactory DVA seismic performance. In this context, some researchers proposed DVA

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implementations by connecting the top floor, or the uppermost top floors, to the rest of the building via isolators, in which case the mass of the top floor(s) becomes the secondary mass [211,212], while others explored the use of distributed multi-TMDs to reduce total secondary mass requirement while suppressing more than one vibration mode [213,214]. However, such solutions are challenging and costly to design and construct. Thus, applications for seismic protection of buildings are currently scarce and are found mostly in regions with seismicity associated with subduction zones, such as the Chilean coast [208]. In these environments, seismic hazard is dominated by large magnitude far-field seismic events inducing long-duration ground motions without pulse-like signatures, in which case DVAs with attached mass of about 5% of the total building mass can efficiently mitigate seismic structural demands [215].

To address the above limitations of DVAs for earthquake engineering applications, new breeds of passive lightweight DVAs have recently emerged for the seismic protection of building structures, in which inertia is mostly endowed by inerter devices rather than secondary mass. The inerter is rigorously defined by Smith [216] as a linear massless mechanical element, resisting relative acceleration by a force proportional to a constant, *b*, termed *inertance* and measured in mass units (kg). Mechanical representations of the three most widely studied inerter-based DVAs in the literature for earthquake engineering applications are shown in Figure 14(a) and include: the tuned mass damper inerter (TMDI) [217] where the inerter amplifies the inertia of the secondary mass, the tuned inerter damper (TID) [218] in which the inerter substitutes the secondary mass, and the tuned viscous mass damper (TVMD) [219] where the inerter acts as a motion amplifier to increase viscous damping capacity. The motion control effectiveness of these DVAs relies on the inertance property, which scales up independently of the inerter device weight. Technologically, this can be achieved by considering rack and pinion or ball-screw mechanisms that transform, through gearing, the translational motion of the device terminals into the rotational motion of a flywheel (*i.e.*, a lightweight fast-spinning disk) [220]. A schematic of a flywheel-based inerter with rack and pinion mechanism and gearing is shown in Figure 14(b), while Figure 14(c) plots inerter force-deformation relationship exhibiting frequency-dependent negative stiffness. Full-scale inerter device prototypes tailored for earthquake engineering applications include ball-screw mechanisms driving electromechanical inertial dampers [221] and TVMDs [222] (Figure 14(d)) as well as hydraulic-pump inerters [223]. These devices can provide inertance of up to 10,000 tons for a gravitational mass of less than 1ton, enabling inertance scalability. Distributed TVMDs have been implemented in a handful of recently completed mid-to-high-rise buildings in Japan [224]).

Recent numerical work demonstrates that TMDI and TID offer significant advantages over conventional mass-based DVAs/TMDs, for seismic protection of fixed-based buildings [207,225–229] and base-isolated buildings [230,231]. These include a reduced weight requirement (by hundreds of tons) for fixed structural performance, enhanced robustness to detuning effects and broadband multi-modal vibrations damping. The latter attribute of inerter-based DVAs enables efficient simultaneous reduction of both storey drifts and floor accelerations demands. This is illustrated in Figure 15(a), which maps structural performance expressed as probability of exceeding code-defined storey-drift and floor acceleration thresholds against DVA control force in a benchmark 9-storey steel frame structure [207]. Additionally, several theoretical works demonstrated that buildings equipped with judicially placed standalone inerters exhibit improved seismic performance by modifying structural inertial properties [232–234]. It was also shown that inertial dampers benefit the seismic response of uplifting structures, as inertance improves the stability of non-deformable rocking blocks [235]. This benefit extends to flexible [236] as well as post-tensioned [237] rocking structures.

Nevertheless, the improved seismic performance achieved by inerter-based DVAs and inertial dampers often comes at the cost of quite high control forces exerted to host structures (*e.g.*, Figure 14(a)). Reducing the magnitude of these forces lies at the forefront of current research and would facilitate practical applications. This issue has been partially addressed in the literature by allowing DVAs to span more than one floor, as seen in Figure 15(b) [207,227], by equipping inerters with one-way clutches and twin flywheels [232,238] and by considering more complex inerter-based DVA layouts than those in Figure 14(a) [239]. Nevertheless, the above solutions increase the complexity of practical implementations, and necessitate further research that compares the cost-efficiency of inerter-based DVAs and devices in different seismogenetic environments. More importantly, structural health monitoring and systematic experimental work involving large/full-scale device testing is necessary for developing field applications and, ultimately, achieving device commercialization for earthquake engineering applications; to date, pertinent work is rather limited (except with regard to the TVMD) [240–242].

As a closure to this section, DVAs can also be used as underground vibrating barriers [243], which were shown, both numerically and experimentally, to seismically protect critical infrastructure and clusters of structures at city-level [244] by leveraging structure-soil-structure interaction. The incorporation of inerters to reduce the required mass and construction cost of vibrating barriers [245] is an open area of promising research towards earthquake resilience that warrants further experimental and field testing.

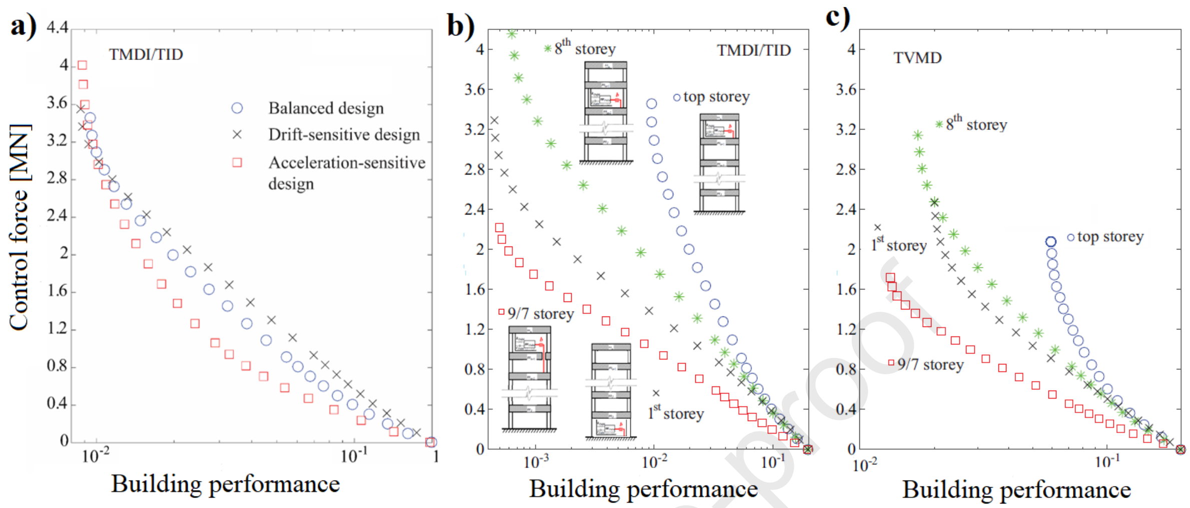

Figure 15. Pareto fronts of optimal inerter-based DVA designs for a 9-storey steel frame building using bi-objective optimization in terms of control force and building performance measured as probability of exceeding storey drift and floor acceleration thresholds (a) Consideration of different EDPs, (b) Consideration of different DVA placements (adapted from Taflanidis *et al.* [207]).

6. SELF-CENTRING & ROCKING SYSTEMS

Large residual drifts can significantly compromise building reparability, leading to high repair costs and disruption of the building use or occupation (*e.g.*, [246]). To address this issue, several research efforts have proposed alternative solutions, which, in addition to controlling the structural damage, enable improvement in the self-centring capabilities of structural systems. Most of these strategies are based on gap opening (*e.g.*, rocking mechanisms), which is controlled by the introduction of elastic restoring forces that are usually provided by high strength post-tensioned steel bars (or strands). These earthquake-resilient structural typologies have been extensively studied during the last decade and some examples include self-centring moment-resisting frames with post-tensioned beam-to-column connections (*e.g.*, [247–250]), column-bases (*e.g.*, [251–254]), rocking walls (*e.g.*, [255]) and self-centring braces (*e.g.*, [256–258]), among others. An overview of most self-centring approaches developed in the last few decades is provided in Cancellor *et al.* [259].

One of the first applications of these concepts is the self-centring brace developed by Christopoulos *et al.* [256], which can return to its original length after undergoing axial elongation or shortening. These braces are based on a self-centring system composed of two concentric tubes pre-compressed by post-tensioned strands and an energy dissipation mechanism facilitated by friction pads. Several other similar devices have been developed in recent years. Researchers (*e.g.*, [257]) have also investigated leveraging the self-centring capability of shape memory alloys within braces to obtain self-centring and dissipative behaviour of the overall device. In these cases, the devices are characterised by the typical flag-shaped hysteretic behaviour shown in Figure 16.

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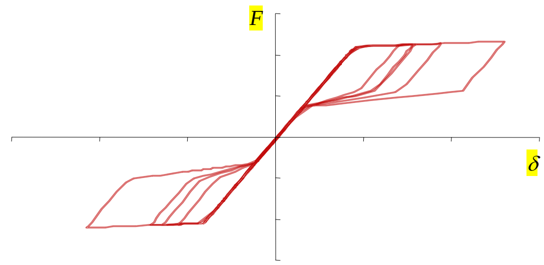

Figure 16. Typical force-displacement (F-δ) flag-shape hysteretic behaviour.

In addition, many recent studies investigated the behaviour of rocking systems. However, some issues related to the use and implementation of rocking systems in practice are still unresolved. Among others, self-centring MRFs are often achieved using damage-free, self-centring devices in beam-to-column connections (*e.g.*, [247–249]) and large attention has been given to the definition of innovative configurations for these components; however, additional studies are required to develop new solutions for low-damage self-centring column bases. These represent fundamental components of the structural system, which significantly affect the seismic behaviour of the structure, (since their member response dominates the performance at a building level) and are difficult to repair or substitute if damaged. Therefore, protecting column bases from damage is an essential requirement of self-centring resilient structures. Several studies have focused on this aspect (*e.g.*, [251–254]), however additional related work is required for to define detailing rules and standard configurations. On the other hand, it is equally important to prevent damage at the column top and/or within the beam-column joint. In a rocking isolation context, the dual solution of a pinned-pinned rocking podium structure has proven promising during recent shaking table tests [260,261].

Another challenge to the practical application of self-centring systems is related to their complexity (and costs) that could significantly exceed those of conventional solutions. To overcome this drawback, current research studies are investigating optimum structural locations that maximise the effectiveness of damage-free self-centring devices. Previous studies on this topic demonstrated that the exclusive use of self-centring damage-free devices at column bases is an effective measure in reducing the residual storey drifts and in protecting the first-storey columns from damage (*e.g.*, [262]). However, the results suggested that this solution is particularly effective for low-rise buildings, while its effectiveness is reduced for medium- and high-rise buildings (*e.g.*, [263]). Significant efforts are required to define economically sustainable solutions for implementing these technologies; determining optimum structural locations for a limited number of damage-free self-centring devices would help towards addressing this challenge.

Other practical issues associated with self-centring systems relate to the floor slab connection of systems with a rocking beam-column connection (*e.g.*, [264]) and to the dynamic behaviour of the flag-shaped system and its potential to generate large floor accelerations (*e.g.*, [265]). Several other challenges exist for these innovative structural systems and there is still a significant need for additional studies that further advance relevant technical knowledge and enable the transfer of academic research to policy making and building codes, thus promoting their application in practice.

7. NON-STRUCTURAL COMPONENTS

Many historic events worldwide have highlighted the significant contribution of non-structural-component damage to earthquake-induced losses in buildings. Although design codes have been modified over the years to address this issue, recent seismic events (*e.g.*, [266–268]) still continue to underline the large economic losses that result from damage of non-structural components, which often largely exceed those due to structural components.

According to Taghavi and Miranda [269], non-structural components and building contents contribute to more than 80% of the total monetary investment in office, hotel and hospital buildings in the United States. Similarly, a FEMA P-58-based study in Italy has shown that the non-structural elements are a major contributor to the expected losses of school buildings [270,271]. Non-structural damage is associated not only with direct losses (as for the case of schools for instance), but also with indirect ones such as loss of functionality and downtime. The indirect impact of non-structural losses was experienced at many hospital complexes affected by the 2016–2017 Central Italy seismic sequence [272]. Located far from the epicentre, these complexes did not suffer structural failure, but significant portions were declared unusable due to damage of non-structural components (*e.g.,* brick coatings, partition walls, and infills).

Infill walls are among the most vulnerable components in buildings, often experiencing damage even under low- to moderate-intensity earthquakes. This is related to the fact that they are assumed to be non-structural components, and are therefore often disregarded in the design, when, in reality, they strongly interact with the building frame. To illustrate the relevance of this problem, the percentage influence of infills on the total repair costs following the L'Aquila Earthquake has been estimated to be of the order of 40-60% [273]. It is noteworthy that damage of infill walls can be related to in-plane or out-of-plane mechanisms and, in many cases to their interaction, with the out-of-plane overturning effects being increased, or even triggered by the in-plane seismic damage. Infill walls and internal partitions are conventionally classified as drift-sensitive structural components. Another category of non-structural components in buildings is represented by those that are damaged during earthquakes when subjected to large acceleration demands rather than high drift demands. This category includes suspended ceilings, parapets, and light fixtures [274,275]. Along with masonry infills, ceiling systems are the most damage-prone non-structural elements during a seismic event [275].

In recent years, with the development of performance-based earthquake engineering, increasing attention has been paid to the seismic risk assessment and mitigation of non-structural components in buildings. For example, in the US, FEMA P-58 provides fragility and consequence functions for estimating the seismic damage to various typologies of non-structural components, such as cladding and glazing systems, elevators, and mechanical, electrical and plumbing systems. FEMA E-74 [276] details survey and mitigation strategies for the reduction of non-structural earthquake damage, tailored to different typologies of non-structural elements. Conversely, European codes do not currently provide specific regulations for the seismic design of infills and ceiling systems; however, Eurocode 8 [131] provides thresholds for maximum inter-storey drifts related to the damage limit state earthquake intensity to protect non-structural elements from damage, while equivalent static forces are used for the design of acceleration-sensitive non-structural components. In addition, some recommendations are given on how to limit infill damage and protect structural components from adverse local effects due to the frame-infill-interaction.

The seismic protection of infill walls is nowadays considered one of the major challenges of earthquake risk mitigation and many research studies are currently focusing on the development of innovative technological solutions to address this issue. Among others, a possible strategy is to increase the resistance of the infill walls, and a significant number of techniques is available for this purpose (*e.g.,* [277,278]). However, this solution often requires the strengthening of frame members adjacent to the infills, significantly affecting its cost-effectiveness.

In recent years, alternative solutions have been proposed for engineered infill walls with enhanced behaviour, exhibiting minimal interaction with the building structural components. In this context, Preti *et al.* [279] developed and tested infill walls with horizontal sliding joints to limit the in-plane infill-frame seismic interaction. A recent study has numerically investigated the benefits of this technique, in terms of reduction of fragility and expected annual losses [280]. Other innovative solutions were proposed and tested within the European Project INSYSME. Vertato *et al.* [281] describes the development and testing of special horizontal rubber joints for the in-plane protection of infills. These joints, originally developed at TARRC (Tun Abdul Razak Research Centre)[11], exhibited an orthotropic behaviour with different stiffness in the three directions [282]. Similar systems were also developed within the same project [283,284].

Numerical modelling of the behaviour of infill panels has also received large attention from the research community, with a wide range of models and approaches proposed (*e.g.,* [285,286]). In this context, Dhir *et al.* [287] developed a computational modelling strategy for describing the non-linear response of masonry infill walls with rubber joints. This strategy, validated against the experimental test carried out by Mehrabi *et al.* [288] on masonry-infilled frames, was employed to describe the benefits of the addition of sliding joints, modelled as zero-thickness interfaces, in terms of: *(a)* minimization of damage to the wall and the frame; and *(b)* reduction of global stiffness of the systems, which has beneficial effects for the seismic performance of acceleration-sensitive components (see Figure 17) (*e.g.,* [289]). Further studies are underway to evaluate the possibility of exploiting the damping properties of the rubber joints to dissipate seismic energy, thus achieving both infill isolation and energy dissipation.

[11] www.tarrc.co.uk

It is noteworthy that the solutions described in Figure 17 for enhanced infill walls do not completely isolate the infills from the frame. The decoupling of the two systems may be obtained by leaving gaps between the infill and frames and filling these gaps with soft material. Alternative solutions have been proposed over the years to provide in-plane isolation while guaranteeing proper restraint in the out-of-plane direction (*e.g.*, [290–292]). However, these solutions are not always cost-effective, and may negatively affect thermal and acoustic isolation.

In recent decades, the seismic design of structures has shifted from a prescriptive-based approach oriented to guarantee life safety and avoid structural collapse, to a performance-based approach, aimed at achieving a better control of the seismic performance. Concepts such as seismic resilience and speed of recovery have become more and more integrated into the design. Moreover, as previously discussed, significant progress has been achieved in the development of seismically isolated buildings and low-damage building components exhibiting minimal seismic damage (*e.g.*, [57,251]). It is envisaged that in the coming years, innovative solutions and design guidelines will make it possible to achieve fully resilient buildings, where not only the structural components, but also the non-structural components and building envelopes, experience minimal damage.

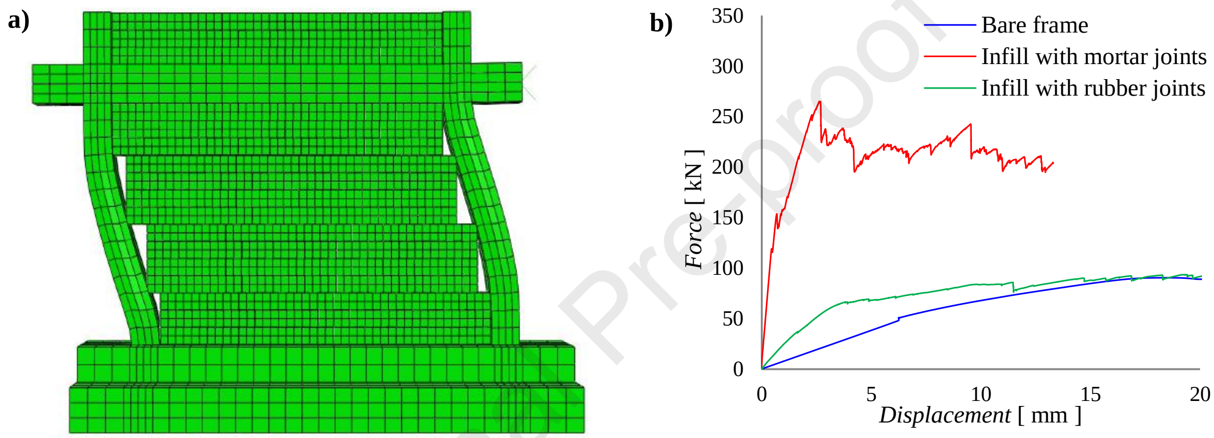

Figure 17. a) Deformed shape of infilled RC frame with horizontal and vertical rubber joints; b) force vs. displacement curve for bare frame and infilled frame, with and without consideration of horizontal rubber joints (adapted from Dhir *et al.* [287]).

In addition to technological developments, this will require significant joint efforts by earthquake engineers, industry trade organizations, contractors, component and material suppliers, building officials, and legislative bodies to address the following needs [293]: *(a)* assessment of the effectiveness of current non-structural design equations and proposal of improved equations if needed. This should also involve instrumenting non-structural components to record their performance during earthquake events and the enhancement of post-earthquake reconnaissance of non-structural components; *(b)* explicit definition of the performance objectives that non-structural components must fulfil; *(c)* improved implementation and enforcement of code requirements for design, installation, and inspection of non-structural components; *(d)* experimental characterization of the performance of non-structural components.

8. STRUCTURAL HEALTH MONITORING

Adequate knowledge of the current state of structural systems is essential in order to properly assess their safety against extreme events and to allow stakeholders and asset managers to take informed decisions for retrofit prioritization and risk reduction interventions. In this context, structural health monitoring (SHM) aims to assess the integrity and performance of engineering structures and infrastructures, either periodically or after specific events, including accidental extreme loading [294]. Recognizing that SHM through visual inspections can be quite subjective, as well as time-consuming, several SHM schemes, relying on various automated sensing modalities and supported by pertinent data post-processing techniques, have emerged in recent decades to facilitate condition assessment of engineering structures [295]. It is also worth noting that integrated EEW and SHM approaches/systems have been proposed in the literature (*e.g.*, [296–298]). These include the use of a Bayesian framework formulation, in which EEW data act as a prior to produce more informed SHM damage estimates.

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Among the SHM schemes detailed in the literature, vibrations-based structural health monitoring (V-SHM) is most widely used for long-term or permanent supervision of large-scale structures, including buildings and bridges, as it is enabled by relatively low-cost acceleration sensors that can be deployed even on existing structures. Typically, V-SHM employs operational modal analysis (OMA) [299] encompassing output-only linear system identification techniques to extract structural dynamic properties, such as natural frequencies, mode shapes, and damping ratios, from response acceleration measurements of structures subjected to non-measured low-amplitude ambient (*e.g.*, wind) or operational (*e.g.*, traffic) excitations. In the context of OMA, these excitations are assumed to be stationary and with a flat spectrum over a wide range of frequencies. Then, *structural damage identification* due to ageing or due to accidental events, including damage existence, localization, and quantification, is often achieved by tracing temporal changes to damage-sensitive indices (DIs), computed from the extracted structural dynamic properties [300].

Over the past two decades, the earthquake engineering community has recognized the potential of long-term V-SHM instrumentation for rapid assessment of civil engineering structures in the aftermath of major seismic events (*e.g.*, [301–303]). These assessments can help with timely decisions on post-earthquake structural safety and integrity and, therefore, improve the resilience of communities against seismic hazard, especially in densely-populated earthquake prone areas (*e.g.*, [304,305]). To this aim, successful earthquake-induced damage identification has been reported in a number of case-studies, using structural response acceleration measurements recorded either during a seismic event (*e.g.*, [306]), or before and after a seismic event (*e.g.*, [307,308]) as graphically depicted in Figure 18(a). Arguably, the former seismic V-SHM strategy that uses data recorded during an earthquake may be challenging for routine applications, as the OMA assumptions are violated: seismic ground motion excitation is transient and non-stationary (time-evolving) both in amplitude and in frequency content (*e.g.*, [309]), while structural response may become non-linear due to structural and non-structural damage. In this setting, traditional OMA techniques need careful application and interpretation (*e.g.*, [310]), while sophisticated approaches beyond OMA are typically required to include joint time-frequency signal analysis (*e.g.*, [306,311,312]) and/or probabilistic Bayesian-based problem treatment [313]. To this end, the seismic V-SHM strategy that uses data recorded before and after an earthquake may more attractive from a practical perspective, as it aligns with standard OMA (*i.e.*, stationary excitation and linear structural response assumptions apply) to estimate DIs before (healthy state) and after (potentially damaged state) the seismic event (Figure 18(a)). In this strategy, the selection of sufficiently accurate, damage-sensitive DIs is a critical consideration for achieving different levels of post-earthquake damage detection (*i.e.*, damage existence, localization, and quantification).

Natural frequencies have historically been the first and most frequently considered DIs in seismic V-SHM applications. Omori (1924) showed, almost a century ago, that the damage caused by an earthquake affects the natural frequencies of buildings. Several recent case-studies (*e.g.*, [307,308,314,315]) estimated shifts in the natural frequencies of various structures, using acceleration measurements before and after damaging earthquakes, and related these shifts to the level of structural damage. Further, Goulet *et al.* [303] developed a data-driven statistical learning framework for predicting, at city-scale, the safety state of buildings based on measured shifts in their natural frequencies and a limited number of inspections. Nevertheless, post-earthquake damage localization at the single-structure level, (*e.g.*, resolving the damaged floor(s) in multi-storey buildings) requires using DIs that incorporate mode-shape information, as has been demonstrated in a number of numerical (*e.g.*, [316,317]) and experimental studies (*e.g.*, [318,319]). An illustrative numerical application of post-earthquake damage localization using the modal curvature DI is shown in Figure 18(b). Still, successful field applications of post-earthquake damage localization using field-recorded data are scarce and further research is warranted to assess the effectiveness of different DIs for the task in real-life structures.

The most important practical challenge that limits the application of long-term V-SHM for structural damage localization is that it requires relatively dense instrumentation (*e.g.*, the application in Figure 18(b) requires one accelerometer per floor), resulting in large up-front and maintenance costs. In this regard, the use of *wireless sensor networks* (WSNs) has been a promising development in V-SHM of civil structures [320] as they reportedly achieve cost reduction of one to two orders of magnitude per sensing channel [321] compared to arrays of wired sensors. In this context, wireless Micro-Electro-Mechanical-Systems (MEMS) accelerometers have been the subject of a number of recent studies (*e.g.*, [322–324]), as they achieve lower phase-shifts at low-frequencies compared to their piezoelectric counterparts [325], while they cost less [326] and consume less power [327]. For example, Rice and Spencer [328] developed a three-axis MEMS device that was employed in the V-SHM of the Basilica Santa Maria of Collemaggio after the L'Aquila earthquake [329]. Pictures of typical wireless MEMS accelerograms are shown in Figure 19(a) [330]. However, various recent studies have highlighted several challenges that still exist in the use of WSN-based V-SHM, beyond seismic or even civil engineering applications, which include: the choice and quality of commercially available sensors [331], their time synchronization within the network [332], the network redundancy in the case of sensor faults [333], electromagnetic interference [330], and data loss [334], as well as energy consumption due to wireless transmission [335–337]. Most of these challenges affect the quality/accuracy of V-SHM, while the last one (energy consumed at sensors primarily during wireless data transmission) relates to V-SHM maintenance cost and environmental impact, as it affects requirements for sensor battery replacement. For illustration, Figure 19(b) shows the relationship between battery lifetime and data transmission compression of a typical wireless acceleration sensor used in long-term V-SHM [337]. Recent approaches for reducing wireless data transmission tailored for seismic V-SHM include the consideration of smart sensor triggering for on-demand measurements at the onset of seismic events, using programmable on-board event-based switching [338] as well as the consideration of compressive sampling schemes for accumulating and transmitting measurements at a small fraction of the Nyquist rate to detect natural frequency shifts due to earthquake damage [339].

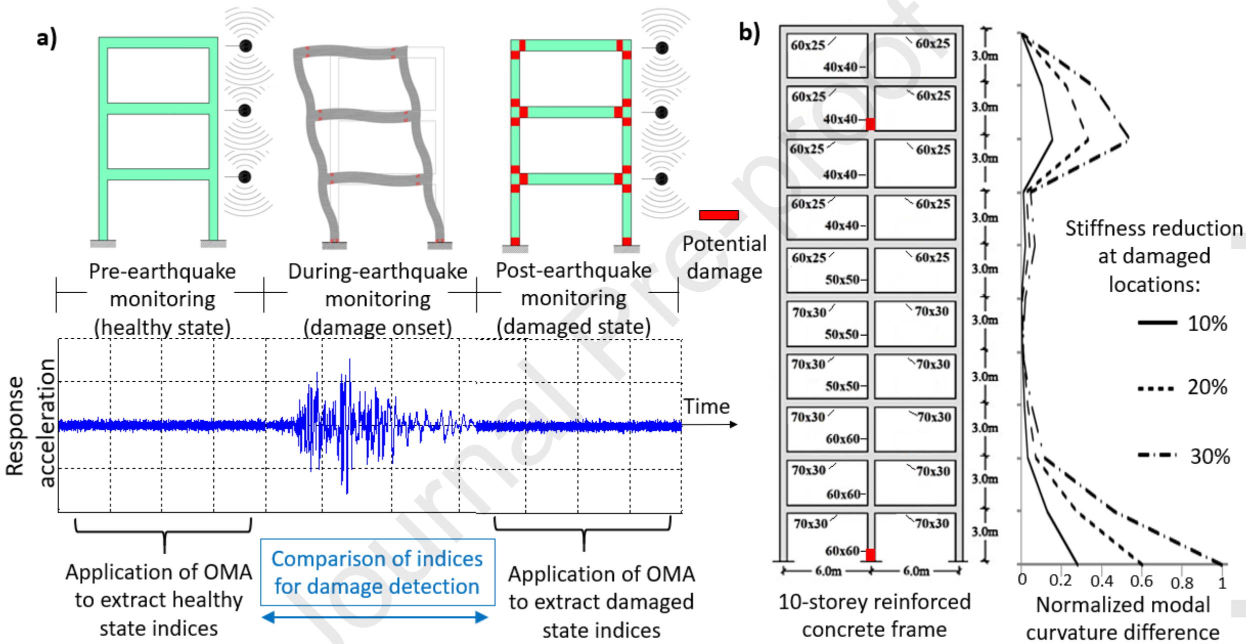

Figure 18. a) Post-earthquake damage detection strategy based on OMA using ambient response acceleration measurements before and after a seismic event; b) Illustration of floor-level damage localization using fundamental mode curvature as damage index in a 10-storey reinforced concrete frame with ground floor and 8th floor base column damage, simulated through local stiffness reduction (adapted from Decarli and Giaralis [317]).

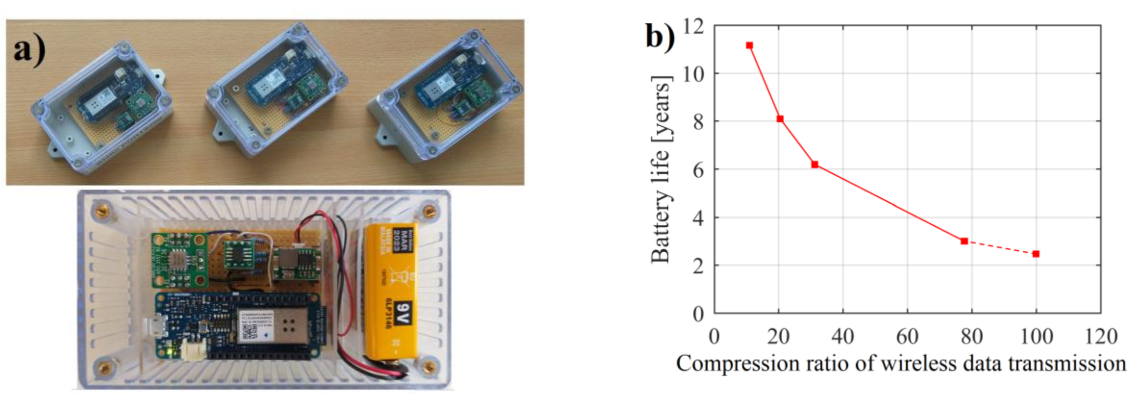

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Figure 19. a) Typical modern wireless acceleration sensing nodes based on low-cost MEMS technology (adapted from Hummel *et al.* [340]). b) Relationship of battery lifetime versus wireless data transmission compression in a typical wireless sensor node used for monitoring a highway overpass (adapted from Gkoktsi and Giaralis [337]).

Despite recent advancements supporting the use of WSNs for general SHM applications [341], more research work is warranted to develop approaches tailored for wireless seismic V-SH,M as well as to assess their effectiveness in real-life deployments. Specifically, improved sensor shielding, better synchronization protocols, and the development of enhanced data processing and transmission methodologies should be at the heart of future efforts. Moreover, further research is warranted to explore SHM modalities beyond V-SHM for rapid and detailed post-earthquake damage detection and assessment as new technologies emerge. Recent preliminary but promising work along these lines include the use of laser-based optical sensors to measure building floor deflections during earthquake excitation [342] as well as the leveraging of global navigation satellite (GPS) measurements [343] and unmanned aerial vehicles (drones) [344] to complement V-SHM modalities. In this context, it becomes evident that data-driven SHM of structural portfolios at city-level scale and/or of large-scale infrastructure and lifelines is essentially a big data problem, which creates opportunities for multi-disciplinary work among different genres of engineers including structural, electrical, and communications engineers as well as computer scientists.

As a closing remark to the section, it is highlighted that financial incentives are essential for achieving widespread deployment of seismic SHM. These incentives, designed to encourage investment in automated SHM for seismic regions by key structure and infrastructure stakeholders (*e.g.,* owners, managers), can help to significantly improve community resilience to earthquake hazard. Meanwhile, the requirements and prescribed level of instrumentation in new construction vary significantly from country to country. Some specific mandates regarding installation, operation and maintenance are enforced in Los Angeles for example [345], while some Latin American countries require the installation of digital accelerographs (*e.g*., [346,347]). In the latter case, significant challenges persist regarding the collection and curation of data. Thus, while the intention may be good, the role of the instrumentation in fostering community resilience against earthquakes is questionable.

9. EARTHQUAKE RISK REDUCTION IN LOW-INCOME COUNTRIES

The above earthquake-related DRR challenges are even more difficult to solve for low-income countries. Firstly, the aforementioned high-tech methods, tools, and devices have to be translated into cost-effective solutions that are easy to be implemented in the local context, and ideally involve materials that can be locally sourced, while also culturally acceptable and co-produced with local communities. Examples of successful translations are low-cost resilient solutions for both pre-earthquake strengthening of buildings [348,349] and seismic isolation. The latter often involves recycled materials (such as rubber from used tyres [350,351]) and the beneficial role of the frictional and damping characteristics of soil and rubber mixtures in the form of a 'geotechnical' seismic isolation of structures [352]. More recently, a Low Cost-Hybrid Design (LC-HD) concept has been developed that leverages the robust design of a superstructure (*i.e.,* one that is able to resist seismic forces up to the design earthquake level, *e.g.*, 0.2g), while a dual PVC-sand foundation layer acts as a 'fuse' once the ground excitation exceeds the design threshold level [353].

A second important challenge that particularly relates to DRR strategies in low-income countries is the scarcity of high-quality data. Therefore, there is a great need for open-source data to be harvested and designed from the beginning within a framework that ensures sustainable management. Similarly, ownership of the developed tools and data infrastructure needs to be transferred to local stakeholders, for long-term impact. This requires the engagement of local policy and decision makers, as well as funding schemes that can facilitate transfer of know-how. Open-source data can also facilitate the application of artificial intelligence and machine learning, which can contribute to filling knowledge gaps in space and time, while identifying patterns that would otherwise be suppressed within the cloud of sporadic information. For instance, in a recent application [354], drone and street-level imagery were fed to machine learning algorithms to automatically detect 'soft-story' buildings or those most likely to collapse in an earthquake. The project was developed by the World Bank's Geospatial Operations Support Team (GOST) in Guatemala City, and is just one of many applications where large amounts of data, processed with machine learning, can have very tangible and consequential impacts on saving lives and property in disasters.

Finally, the resilience of infrastructure and communities is also key for quick recovery after a major seismic event in low-income countries. Given *(a)* the very low penetration of insurance in these regions, *(b)* the high

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vulnerability and low quality of construction, and *(c)* the limited resources to accelerate recovery, losses associated with major earthquakes tend to be disproportionally high compared to other regions of the world. Thus, it is of paramount importance that we promote strategies that can help the local population to bounce back stronger, which requires disaster awareness, enhanced building quality and seismic performance, as well as community capacity building to cope with the disaster and its associated stresses. In this light, quantification of infrastructure resilience (in the form of 'hard' metrics) and assessment of community resilience [355], in a mixed qualitative and quantitative way [356] should be major drivers for improving the current state of DRR, as recognised by the SFDRR.

10. CONCLUSIONS

Five years after the *Sendai Framework for Disaster Risk Reduction 2015–2030* was adopted, its implementation is delivering results. Many countries have increased their capacity to facilitate disaster risk reduction (DRR) programmes and progress has been made in saving lives and livelihoods through investments in disaster preparedness and response. However, action to prevent the creation of new risks and to reduce existing disaster risk is still lacking. Science and technology have a crucial role to play in addressing this issue.

To share knowledge and promote discussion on recent advances, challenges, and future directions on *'Innovations in Earthquake Risk Reduction and Resilience'*, a group of experts from both academia and industry met in London, UK, in July 2019. The workshop focused on both cutting-edge *'soft'* risk-reduction strategies (*e.g.,* novel modelling frameworks, early warning systems, disaster financing and parametric insurance) and *'hard'* (*e.g.,* use of innovative structural devices, sensors, novel structural systems for new structures and retrofitting of existing structures) for the enhancement of structural and infrastructural safety and resilience.

Key highlights from the workshop include:

1) 3D physics-based ground motion simulations represent a viable alternative to empirical ground-motion models (GMMs) outputs for capturing earthquake hazard (and therefore risk) in both research and practice. Yet, there are a number of challenges that need to be tackled for a full implementation of a physics-based approach in large-scale seismic risk modelling. For example, the simulations require long pre-processing and execution times and specific expertise for their implementation. In addition, the lower predictive power of simulated ground motions in the high-frequency range represents another obstacle to their use in large-scale regional risk assessments. Finally, understanding and capturing all potential sources of ground-motion uncertainty and constraining all input parameters within reasonable bounds is an on-going research endeavour, which is crucial for accurately representing seismic hazard and resulting economic and social losses.

2) It always remains necessary to better understand the performance of earthquake loss model predictions relative to actual consequences from seismic events, so that appropriate advancements can continually be made in the underlying methodologies. For structure-specific loss models, validation efforts require high resolution seismic loss data, ideally from assets in regions where most of the information used to develop the corresponding methodology originates, which is often difficult to obtain. To address this challenge, post- earthquake data collection methods should be developed with required loss-model validation data in mind. The important role of structure-specific repair time predictions in decision-making could be significantly improved if they were applied within seismic resilience assessment frameworks that also account for non-engineering factors beyond the asset footprint. These frameworks should be probabilistic in nature and have the ability to mathematically unify downtime predictions for both physical and non-physical systems, so that dynamic variations of post-earthquake recovery can be quantified and assessed by relevant stakeholders.

3) There is a significant need for innovative frameworks and detailed studies focusing on the simultaneous and/or sequential effects of multiple hazards to better understand and model cascading consequences. Some challenges in this area are represented by the temporal variability in the occurrence of different hazard effects and the need to consider the appropriate timing of restoration strategies. Moreover, there is a significant need for region-specific studies that provide better characterisations of the relationship between physical loss and loss of functionality, allowing more reliable estimates and interdependencies between direct and indirect losses. In infrastructure facilities, this is often dependent on decision-making policies and communication strategies and how these are being regulated/standardised and implemented by consultants, government and governmental bodies, local authorities, designers, and assessors, which should be properly standardised.

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3) Emerging technologies and improved data processing capabilities continue to pave the way for increasingly streamlined and efficient risk-transfer tools in the catastrophe insurance market. For example, the inception of 'smart contracts' built on blockchain technology are facilitating the creation of more transparent insurance policies that enable expedited payouts. Big data analytics and artificial intelligence have significant potential to enhance the performance of parametric insurance products by contributing to the development of more reliable trigger mechanisms that minimise basis risk. However, it is important to note that the capabilities of the underlying algorithms are directly dependent on the quality of the input data. It will be particularly interesting to see how novel computational approaches evolve going forward, and how parametric insurance practices advance in parallel.

4) Earthquake early warning (EEW) is a relatively new innovation in DRR, with clear potential to enhance societal recovery from earthquake disasters. To maximise the effectiveness of EEW as a viable tool for seismic resilience promotion, there needs to be a greater research focus on its decision-support capabilities, from both a technical and a socio-organisational standpoint. The creation of next-generation 'people-centred' EEW with risk-informed decision-making capacity will require the collection and integration of appropriate state-of-the-art contributions from the fields of seismology, engineering, decision science, and social science.

5) Passive control systems (*e.g.*, seismic isolation and damping devices), for the reduction of seismic actions on construction, have been extensively studied during the past few decades, creating new opportunities to design more resilient structures and infrastructure. However, while design strategies are well consolidated in the case of traditional solutions (*e.g.,* capacity design, safety factors), and have demonstrated their capabilities with respect to exceptional events, additional investigations in this context are required for seismic isolation and supplemental damping systems, and many studies are currently on-going on these topics. For example, although systems that use innovative devices are very efficient in reducing damage and have a reliable response thanks to quality control tests, they often show a brittle behaviour that may strongly reduce global robustness in the case of extreme and rare seismic actions. This highlights the need for additional studies on the adequate choice of safety coefficients related to required reliability levels. Additional studies on this research area are related to the development of dynamic vibration absorbers and inertial dampers, which represent promising structural control solutions, as well as self-centring and damage-free systems. Although some studies have demonstrated the feasibility and effectiveness of these systems, further research is needed to define optimized solutions and design methodologies that facilitate integration of related academic research in policy making and building codes, hence promoting the application of these solutions in practice.

6) Damage to non-structural components and building contents often results in the majority of total direct event losses for building structures and significantly contributes to the loss of functionality and downtime. Thus, reducing the vulnerability of non-structural components is crucial for achieving fully earthquake-resilient buildings. Among other examples, the protection of infill walls is nowadays considered one of the major challenges of earthquake risk mitigation and many research studies are addressing the issue. This issue provides a unique opportunity to develop technological solutions that not only reduce the infill vulnerability, but also enhance the global performance of the whole structure through additional sources of damping.

7) Adequate knowledge on the current state of structural systems is essential to properly assess their safety against extreme events and to allow stakeholders and asset managers to take informed decisions for retrofit prioritization and risk reduction interventions. In this context, structural health monitoring (SHM) aims to assess the integrity and performance of engineering structures and infrastructures. Many studies have focused on the SHM research area, however, there are still several issues to address before these tools can be widely applied in practice. Challenges relate to the storage, integration, and deployment of heterogenous data, latent information and evidence in rapid decision making. Another issue is the current lack of regulations/alliances that support SHM in providing warnings and risk/resilience quantifications at component-, asset-, and network-level. Generally, not enough is being done at the moment to embrace emerging digital technologies in earthquake DRR.

8) Risk modelling and innovative DRR technologies for low-income countries are particularly challenging due to the scarcity of high-quality data, availability of specific materials, and the need for cost-effective solutions. It is also crucial to promote robust DRR in these regions through improved data collection, assessing the full spectrum of natural hazards, and considering different structures and infrastructure systems, ensuring that risk models are contextualised to local conditions.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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